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A dynamic inexact energy systems planning model for supporting greenhouse-gas emission management and sustainable renewable energy development under uncertainty—A case study for the City of Waterloo, Canada

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ABSTRACT

In this study, a dynamic interval-parameter community-scale energy systems planning model (DIP-CEM) was developed for supporting greenhouse-gas emission (GHG) management and sustainable energy development under uncertainty. The developed model could reach insight into the interactive characteristics of community-scale energy management systems, and thus capable of addressing specific community environmental and socio-economic features. Through integrating interval-parameter and mixed-integer linear programming techniques within a general optimization framework, the DIP-CEM could address uncertainty (expressed as interval values) existing in related costs, impact factors and system objectives as well as facilitate dynamic analysis of capacity-expansion decisions under such a uncertainty. DIP-CEM was then applied to the City of Waterloo, Canada to demonstrate its applicability in supporting decisions of community energy systems planning and GHG-emission reduction management. One business-as-usual (BAU) case and two GHG-emission reduction cases were analyzed with desired plans of GHG-emission reduction. The results indicated that the developed DIP-CEM could help provide sound strategies for dealing with issues of sustainable energy development and GHG-emission reduction within an energy management system.

Contents

1. Introduction

Growing population, booming economy and changing climate are expected to exert significant challenges towards community-scale energy systems. Energy systems planning is essential to deal with these challenges [1]. However, such a planning exercise is highly complicated, involving a large number of social, economic, environmental, technical, and political factors and their interactions, coupled with complex temporal and spatial variabilities and cascading effects [2]. Moreover, climate change concerns necessitate the consideration of greenhouse-gas (GHG) emission reduction within energy management systems [3,4]. These emphasize the need of an effective systems analysis approach for supporting the planning of such complex systems.

Previously, considerable efforts were made to develop energy systems planning models, such as the Model for Energy Supply

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Strategy Alternatives and their General Environmental Impact (MESSAGE) [5], and Market Allocation Model (MARKAL) [6,7]. These models and their subsequent versions were used for supporting national, regional and municipal energy systems planning and environmental management [8,9]. In addition, Kambo et al. conducted a modeling study for the City of Delhi, India [10]. Haurie presented a MARKAL-Lite model for the municipal energy system in Geneva, Switzerland, with a focus on industrial activities [11]. Richter and Hamacher developed a municipal model for Augsburg, Germany [12]. Nilsson and Martensson proposed a municipal energy systems planning model to study various municipal energy plans in southern Sweden [13]. Li et al. reported a study on the development of municipal energy supply planning model for the City of Hohhot, China [14]. Kaewniyompanit et al. conducted a modeling study with a focus on power supply variations in Japan [15]. Lin et al. developed an energy systems planning model to study the GHG-emission reduction policies and climate change impacts in Toronto-Niagara Region, Canada [16]. Cai et al. applied UREM model to the Region of Waterloo [17].

However, most of the previous studies limited themselves to energy systems planning from a national, provincial or municipal perspective. They could hardly reach insight into the interactive characteristics of energy-related activities at a community level, and thus were unable to address the unique environmental and socio-economic features of community-scale energy management systems. The previous studies on community-scale energy systems primarily focused on individual sectors rather than the entire system, being unable to provide a holistic analysis of various interactions among multiple energy sectors. In addition, the uncertainties (expressed as interval values) existing in the related costs, impact factors and system objectives and dynamics of facility expansion related to issues of timing, sizing and siting under such a uncertainty were not effective addressed in the previous studies [18–22].

Therefore, the objective of this study is to develop a dynamic interval-parameter community-scale energy systems planning model (DIP-CEM) through integrating mixed-integer and interval-parameter linear programming (ILP) within an optimization framework. This objective entails the following tasks:

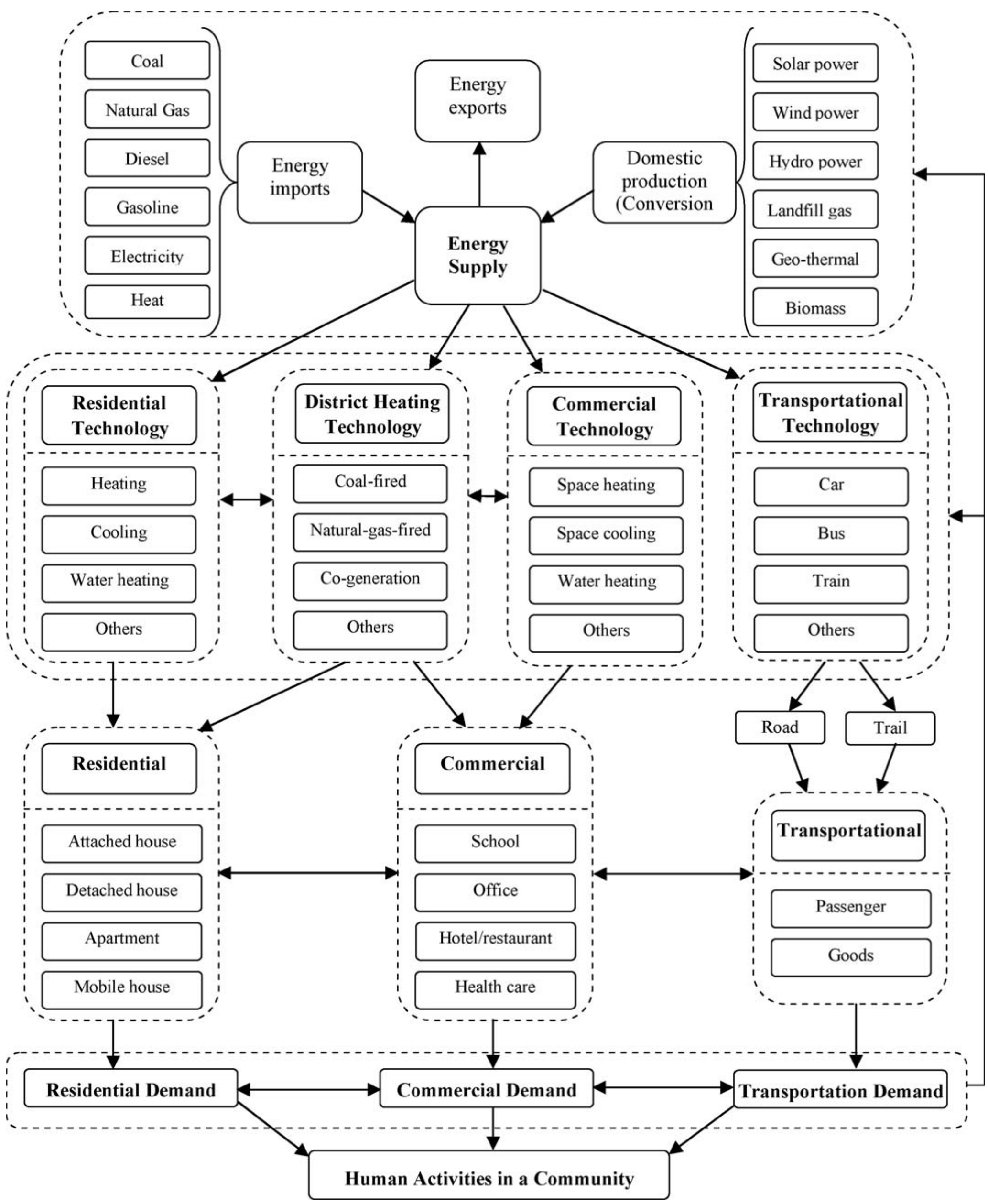

Fig. 1. Diagram of community-scale energy management systems.

(1) Development of a community-scale energy systems planning model (CEM) to help explore opportunities for the development of energy-saving residential, commercial and transportational facilities, and the utilization of local renewable energy resources.
(2) Integration of interval-parameter and mixed-integer linear programming (MILP) techniques into the developed CEM to formulate the DIP-CEM for tackling uncertainties expressed as interval numbers and addressing dynamics of facility-expansion issues.
(3) Application of DIP-CEM to the City of Waterloo, Canada, to demonstrate its capability in supporting sustainable energy development and GHG-emission management within community-scale energy management systems.

2. Development of DIP-CEM

Community-scale energy management systems are related to a number of energy supply, conversion and demand activities and various cost-effective demand-side management programs, such as district heating and cooling, mass transportation, heat and power co-generation, renewable energy utilization, and building insulation improvement (Fig. 1). In such systems, many modeling parameters and system objectives may only be available as intervals. Such uncertain information needs to be reflected in an optimization framework. In addition, dynamics of capacity-expansion issues need to be tackled, and concerns of GHG-emission reduction need to be addressed. Therefore, a DIP-CEM that integrates ILP and MILP techniques is desired for dealing with complexities. The ILP is effective in handling interval-format uncertainties in both the right- and left-hand sides of the constraints as well as the coefficients in the objective function [23,24]; MILP can tackle dynamics of facility-expansion in energy management systems [25]. Planning of community-scale energy systems lead to the development of DIP-CEM with the objective function being minimized total system cost subject to a variety of constraints.

2.1. Modeling formulation

The objective function of the DIP-CEM consists of costs of energy supply, conversion and end-utilization, as well as capacity expansion. The decision variables can be classified into two types: binary and continuous. The binary variables are dedicated to address capacity-expansion options; the continuous ones are committed to reflect other energy-related activities. The objective of DIP-CEM is to minimize the total system costs, and its function can be formulated as follows:

$$
\begin{aligned}
Min\ & \sum_t \sum_s \sum_{ee} \sum_w XIS^{\pm}_{t,s,ee,w}\left(IP^{\pm}_{t,s,ee,w} + \sum_e DELI^{\pm}_{t,s,e,w,ee} INPI^{\pm}_{t,s,e,w,ee}\right) - \sum_t \sum_s \sum_{ee} \sum_w XES^{\pm}_{t,s,ee,w}\left(EP^{\pm}_{t,s,ee,w} - \sum_e DELE^{\pm}_{t,s,e,w,ee} INPE^{\pm}_{t,s,e,w,ee}\right) \\
& + \sum_t \sum_s \sum_w XIE^{\pm}_{t,s,w} IPE^{\pm}_{t,s,w} + \sum_t \sum_s \sum_w YCE^{\pm}_{t,s,w,op} CET^{\pm}_{t,s,w,op} ETIN^{\pm}_{t,s,w,op} + \sum_t \sum_s \sum_w \left(CRDE^{\pm}_{t,s,w} + \sum_{t=2} YCE^{\pm}_{t-1,s,w,op} CET^{\pm}_{t-1,s,w,op}\right) TEFIX^{\pm}_{t,s,w} \\
& - \sum_t \sum_s \sum_w XEE^{\pm}_{t,s,w} EPE^{\pm}_{t,s,w} + \sum_t \sum_s \sum_w XIH^{\pm}_{t,s,w} IPH^{\pm}_{t,s,w} + \sum_t \sum_s \sum_w YCH^{\pm}_{t,s,w,op} CHT^{\pm}_{t,s,w,op} HTIN^{\pm}_{t,s,w,op} \\
& + \sum_t \sum_s \sum_w \left(CRDH^{\pm}_{t,s,w} + \sum_{t=2} YCH^{\pm}_{t-1,s,w,op} CHT^{\pm}_{t-1,s,w,op}\right) THFIX^{\pm}_{t,s,w} - \sum_t \sum_s \sum_w XEH^{\pm}_{t,s,w} EPH^{\pm}_{t,s,w} \\
& + \sum_t \sum_s \sum_r XP^{\pm}_{t,s,r}\left(VRC^{\pm}_{t,s,r} + \sum_e DEL^{\pm}_{t,s,r,e} INP^{\pm}_{t,s,r,e}\right) + \sum_t \sum_s \sum_p XE^{\pm}_{t,s,p}\left(VRE^{\pm}_{t,s,p} + \sum_{ee} DEL^{\pm}_{t,s,p,ee} INP^{\pm}_{t,s,p,ee}\right) \\
& + \sum_t \sum_s \sum_p YCE^{\pm}_{t,s,p,op} CET^{\pm}_{t,s,p,op} ETIN^{\pm}_{t,s,p,op} + \sum_t \sum_s \sum_p \left(CRDE^{\pm}_{t,s,p} + \sum_{t=2} YCE^{\pm}_{t-1,s,p,op} CET^{\pm}_{t-1,s,p,op}\right) TEFIX^{\pm}_{t,s,p} \\
& + \sum_t \sum_s \sum_p YCH^{\pm}_{t,s,p,op} CHT^{\pm}_{t,s,p,op} HTIN^{\pm}_{t,s,p,op} + \sum_t \sum_s \sum_p \left(CRDH^{\pm}_{t,s,p} + \sum_{t=2} YCH^{\pm}_{t-1,s,p,op} CHT^{\pm}_{t-1,s,p,op}\right) THFIX^{\pm}_{t,s,p} \\
& + \sum_t \sum_s \sum_h XH^{\pm}_{t,s,h}\left(VRH^{\pm}_{t,s,h} + \sum_e DEL^{\pm}_{t,s,h,e} INP^{\pm}_{t,s,h,e}\right) + \sum_t \sum_s \sum_h YCH^{\pm}_{t,s,h,op} CHT^{\pm}_{t,s,h,op} HTIN^{\pm}_{t,s,h,op} \\
& + \sum_t \sum_s \sum_h \left(CRDH^{\pm}_{t,s,op} + \sum_{t=2} YCH^{\pm}_{t-1,s,h,op} CHT^{\pm}_{t-1,s,h,op}\right) THFIX^{\pm}_{t,s,h} + \sum_t \sum_s \sum_a \left(CRDA^{\pm}_{t,s,a} + \sum_{t=2} XCA^{\pm}_{t-1,s,a}\right) FIX^{\pm}_{t,s,a} \\
& + \sum_t \sum_s \sum_a XCA^{\pm}_{t,s,a} INC^{\pm}_{t-1,s,a} + \sum_t \sum_s \sum_b \left(CRDB^{\pm}_{t,s,b} + \sum_{t=2} YCB^{\pm}_{t-1,s,b,op} INC^{\pm}_{t-1,s,b,op}\right) FIX^{\pm}_{t,s,b} + \sum_t \sum_s \sum_b YCB^{\pm}_{t-1,s,b,op} CB^{\pm}_{t-1,s,b,op} INC^{\pm}_{t-1,s,b,op} \\
& + \sum_t \sum_s \sum_z \sum_y \sum_m \sum_n XD^{\pm}_{t,s,z,y,m,n}\left(\sum_{eh} DEL^{\pm}_{t,s,z,y,m,n,eh} INP^{\pm}_{t,s,z,y,m,n,eh}\right) + \sum_t \sum_s \sum_z \sum_y \sum_i XSE^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}spc\text{'},i} CES^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}spc\text{'},i} \\
& + \sum_t \sum_s \sum_z \sum_y \sum_j XSR^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m=\text{`}spc\text{'},j} CER^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}spc\text{'},j} \\
& + \sum_t \sum_s \sum_{cz} \sum_{cy} \sum_{cm} \sum_{cn} XD^{\pm}_{t,s,cz,cy,cm,cn}\left(VRC^{\pm}_{t,s,cz,cy,cm,cn} + \sum_{eh} DEL^{\pm}_{t,s,cz,cy,cm,cn,eh} INP^{\pm}_{t,s,cz,cy,cm,cn,eh}\right) \\
& + \sum_t \sum_s \sum_v XDTI^{\pm}_{t,s,v} \sum_e INP^{\pm}_{t,s,v,e} AVL^{\pm}_{t,s,v} DELT^{\pm}_{t,s,v,e} + \sum_t \sum_s \sum_v \sum_o XDTE^{\pm}_{t,s,v,o,c} AVK^{\pm}_{t,s,v,o} \sum_e INPR^{\pm}_{t,s,v,o,c,e} DELT^{\pm}_{t,s,v,o,e} \\
& + \sum_t \sum_s \sum_u XDTI^{\pm}_{t,s,u} AVL^{\pm}_{t,s,u}\left(VRC^{\pm}_{t,s,u} + \sum_e INP^{\pm}_{t,s,u,e} DELT^{\pm}_{t,s,u,e}\right) + \sum_t \sum_s \sum_u \sum_o XDTE^{\pm}_{t,s,u,o,c} AVK^{\pm}_{t,s,u,o}\left(VRC^{\pm}_{t,s,u,o} + \sum_e INPR^{\pm}_{t,s,u,o,c,e} DELT^{\pm}_{t,s,u,o,e}\right) \\
& + \sum_t \sum_s \sum_d \left(CRDB^{\pm}_{t,s,d} + \sum_{t=2} YCB^{\pm}_{t-1,s,d,op} INC^{\pm}_{t-1,s,d,op}\right) FIX^{\pm}_{t,s,d} + \sum_t \sum_s \sum_d YCB^{\pm}_{t-1,s,d,op} CB^{\pm}_{t-1,s,d,op} INC^{\pm}_{t-1,s,d,op}
\end{aligned}
\tag{2.1.1}
$$

The objective of DIP-CEM subject to various economic, technical and environmental constraints, including demand constraints, mass balance constraints, capacity constraints, emission constraints and other technical constraints. The demand-related activities usually account for the largest energy consumption in community-scale energy systems. According to user type, these activities are further classified into residential, commercial and transportation sectors. The residential demand is primarily related to household activities (sufficient housing is required to meet residential living). Households are equipped with devices for space heating, space cooling, lighting, cooking, water heating and others. The total outputs from these devices are required to be greater than the total residential energy demands. Moreover, options that can reduce such demands, such as the use of energy-saving materials for building construction, and insulation improvement of the existing houses, are also considered. The addition of new devices, as well as new buildings to meet increasing residential demands, would become necessary when the existing devices are insufficient. The constraints describing energy demands for residential activities are presented as follows:

- Constraints for new housing:

$$\sum_n XD^{\pm}_{t,s,z,y=\text{`}nb\text{'},m\neq\text{`}shc\text{'},n} EOUT^{\pm}_{t,s,z,y=\text{`}nb\text{'},m\neq\text{`}shc\text{'},n} \geq DMR^{\pm}_{t,s,z,y=\text{`}nb\text{'},m\neq\text{`}shc\text{'}} \tag{2.1.2a}$$

$$\sum_n XD^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}shc\text{'},n} EOUT^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}shc\text{'},n} + \sum_i XSE^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}shc\text{'},i} ESR^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}shc\text{'},i} \geq DMR^{\pm}_{t,s,z,y=\text{`}nb\text{'},m=\text{`}shc\text{'}} \tag{2.1.2b}$$

- Constraints for the existing housing:

$$\sum_n XD_{t,s,z,y\neq\text{`}nb\text{'},m\neq\text{`}shc\text{'},n} EOUT^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m\neq\text{`}shc\text{'},n} \geq DMR^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m\neq\text{`}shc\text{'}} \tag{2.1.2c}$$

$$\sum_n XD^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m=\text{`}shc\text{'},n} EOUT^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m=\text{`}shc\text{'},n} + \sum_j XSR^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m=\text{`}shc\text{'},j} ESR^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m=\text{`}shc\text{'},j} \geq DMR^{\pm}_{t,s,z,y\neq\text{`}nb\text{'},m=\text{`}shc\text{'}} \tag{2.1.2d}$$

For energy-related commercial activities, the users can be further classified into such sub-group as school, hospital, office, retail outlet and hotel according to the types of commercial services provided. Similar to the residential sector, the current commercial demands are calculated based on the existing building and service provided in the community. When the existing device capacities are insufficient in meeting the demands, additional capacity may be required. The constraints defining these relationships can be formulated as follows:

$$\sum_{cn} XD^{\pm}_{t,s,cz,cy,cm,cn} EOUT^{\pm}_{t,s,cz,cy,cm,cn} \geq DMC^{\pm}_{t,s,cz,cy,cm} \tag{2.1.2e}$$

Energy demands related to transportational activities in a community-scale energy system are modeled in two parts: internal and external. The internal demands address activities within residential and commercial regions. The external demands reflect activities beyond the regions or the connected major residential and commercial centers; due to the limited infrastructure connecting residential and commercial areas or outside the community, the transportational activity is primarily determined by both vehicle type and road layout. Each vehicle will have unique energy efficiency through a specific path, provided variations exist in road length and average speed. When the existing infrastructure cannot support the transportation activities with acceptable speed and energy efficiency, new roads or new modes of transportation will be developed. The internal transportation demands are formulated in Eqs. (2.1.2f) and (2.1.2g), and the external demands are formulated in Eqs. (2.1.2h) and (2.1.2i).

$$\sum_v XDTI^{\pm}_{t,s,v} PPVI^{\pm}_{t,s,v} \geq POTI^{\pm}_{t,s} \tag{2.1.2f}$$

$$\sum_u XDTI^{\pm}_{t,s,u} PPVI^{\pm}_{t,s,u} \geq GOTI^{\pm}_{t,s} \tag{2.1.2g}$$

$$\sum_v XDTE^{\pm}_{t,s,v} PPVE^{\pm}_{t,s,v} \geq POTE^{\pm}_{t,s} \tag{2.1.2h}$$

$$\sum_u XDTE^{\pm}_{t,s,u} PPVE^{\pm}_{t,s,u} \geq GOTE^{\pm}_{t,s} \tag{2.1.2i}$$

Commonly, typical community-scale energy systems contain minor fossil energy production and processing activities. Supply of energy such as gasoline, diesel and electricity basically relies on imports. Central heat generation from fossil energy accounts for an option for commercial and residential space heating, and is thus a necessary consideration for the study system. The constraints related to energy supply and conversion can thus be presented in the following equations:

- Mass balance constraints of electricity:

$$\begin{aligned}
&\sum_w XIE^{\pm}_{t,s,w} - \sum_w XEE^{\pm}_{t,s,w} + \sum_p XE^{\pm}_{t,s,p} - \sum_r XP^{\pm}_{t,s,r} INP^{\pm}_{t,s,r,\text{`}ele\text{'}} \\
&- \sum_h XH^{\pm}_{t,s,h} INP^{\pm}_{t,s,h,\text{`}ele\text{'}} - \sum_z \sum_y \sum_m \sum_n XD^{\pm}_{t,s,z,y,m,n} INP^{\pm}_{t,s,z,y,m,n,\text{`}ele\text{'}} \\
&- \sum_{cz} \sum_{cy} \sum_{cm} \sum_{cn} XD^{\pm}_{t,s,cz,cy,cm,cn} INP^{\pm}_{t,s,cz,cy,cm,cn,\text{`}ele\text{'}} \\
&- \sum_v XDTI^{\pm}_{t,s,v} INP^{\pm}_{t,s,v,\text{`}ele\text{'}} AVL^{\pm}_{t,s,v} - \sum_u XDTI^{\pm}_{t,s,u} INP^{\pm}_{t,s,v,\text{`}ele\text{'}} AVK^{\pm}_{t,s,v} \\
&- \sum_v \sum_o XDTE^{\pm}_{t,s,v,o} INPR^{\pm}_{t,s,v,c,\text{`}ele\text{'}} AVL^{\pm}_{t,s,v,o} \\
&- \sum_u \sum_o XDTE^{\pm}_{t,s,u,o} INPR^{\pm}_{t,s,u,c,\text{`}ele\text{'}} AVL^{\pm}_{t,s,u,o} \geq 0
\end{aligned} \tag{2.1.3a}$$

- Mass balance constraints of energy carriers (excluding electricity and heat):

$$\begin{aligned}
&\sum_w XIS^{\pm}_{t,s,ee,w} - \sum_w XES^{\pm}_{t,s,ee,w} - \sum_{ae} \sum_w XIS^{\pm}_{t,s,ee,ae,w} INPI^{\pm}_{t,s,ee,ae,w} \\
&- \sum_{ae} \sum_w XES^{\pm}_{t,s,ee,ae,w} INPE^{\pm}_{t,s,ee,ae,w} - \sum_r XP^{\pm}_{t,s,r} INP^{\pm}_{t,s,r,ee} \\
&+ \sum_r XP^{\pm}_{t,s,r} OUT^{\pm}_{t,s,r,ee} - \sum_p XE^{\pm}_{t,s,p} INP^{\pm}_{t,s,p,ee} - \sum_h XH^{\pm}_{t,s,h} INP^{\pm}_{t,s,h,ee} \\
&- \sum_z \sum_y \sum_m \sum_n XD^{\pm}_{t,s,z,y,m,n} INP^{\pm}_{t,s,z,y,m,n,ee} \\
&- \sum_{cz} \sum_{cy} \sum_{cm} \sum_{cn} XD^{\pm}_{t,s,cz,cy,cm,cn} INP^{\pm}_{t,s,cz,cy,cm,cn,ee} \\
&- \sum_v XDTI^{\pm}_{t,s,v} INP^{\pm}_{t,s,v,ee} AVL^{\pm}_{t,s,v} - \sum_u XDTI^{\pm}_{t,s,u} INP^{\pm}_{t,s,u,ee} AVK^{\pm}_{t,s,u} \\
&- \sum_v \sum_o XDTE^{\pm}_{t,s,v,o} INPR^{\pm}_{t,s,v,c,ee} AVL^{\pm}_{t,s,v,o} \\
&- \sum_u \sum_o XDTE^{\pm}_{t,s,u,o} INPR^{\pm}_{t,s,u,c,ee} AVK^{\pm}_{t,s,u,o} \geq 0
\end{aligned} \tag{2.1.3b}$$

- Mass balance constraints of heat:

$$\begin{aligned}
&\sum_w XIH^{\pm}_{t,s,w} - \sum_w XEH^{\pm}_{t,s,w} + \sum_h XH^{\pm}_{t,h} + \sum_p XE^{\pm}_{t,s,p} COH^{\pm}_{t,s,p,\text{`}h\text{'}} \\
&- \sum_z \sum_y \sum_{m=\text{`}sh\text{'}} \sum_{n=\text{`}ch\text{'}} XD^{\pm}_{t,s,z,y,m,n} INP^{\pm}_{t,s,z,y,m,n} \\
&- \sum_{cz} \sum_{cy} \sum_{cm=\text{`}sh\text{'}} \sum_{cn=\text{`}ch\text{'}} XD^{\pm}_{t,s,cz,cy,cm,cn} INP^{\pm}_{t,s,cz,cy,cm,cn} \geq 0
\end{aligned} \tag{2.1.3c}$$

The capacity constraints are formulated to secure sufficient capacities for satisfying production of a given energy or service. Four groups of capacity constraints are established according to technology types (electricity conversion, heat generation, energy processing, and energy demand technologies). The decision variables representing capacity-expansion options are binary. The expanded and existing capacities are considered the total in service. For each technology, the amount of its output or production should be less than that the total installed capacity. If this requirement is violated, additional capacities will be needed. The constraints are elaborated as follows:

$$\left(CRD^{\pm}_{t,s,z,y,m,n}+\sum_{t=2}XCA^{\pm}_{t-1,s,z,y,m,n}\right)AF^{\pm}_{t,s,z,y,m,n}\geq XD^{\pm}_{t,s,z,y,m,n} \quad (2.1.4a)$$

$$\left(CRD^{\pm}_{t,s,cz,cy,cm,cn}+\sum_{t=2}XCA^{\pm}_{t-1,s,cz,cy,cm,cn}\right)AF^{\pm}_{t,s,cz,cy,cm,cn}\geq XD^{\pm}_{t,s,cz,cy,cm,cn} \quad (2.1.4b)$$

$$\left(CRD^{\pm}_{t,s,v}+\sum_{t=2}XCA^{\pm}_{t-1,s,v}\right)\geq XDTI^{\pm}_{t,s,v} \quad (2.1.4c)$$

$$\left(CRD^{\pm}_{t,s,u}+\sum_{t=2}XCA^{\pm}_{t-1,s,u}\right)\geq XDTI^{\pm}_{t,s,u} \quad (2.1.4d)$$

$$\sum_{o}\left(CRD^{\pm}_{t,s,o}+\sum_{t=2}YCB^{\pm}_{t-1,s,o,op}CB^{\pm}_{t-1,s,o,op}\right)AF^{\pm}_{t,s,o}\geq\sum_{v\neq l}XDTE^{\pm}_{t,s,v}+\sum_{u}XDTE^{\pm}_{t,s,u} \quad (2.1.4e)$$

$$\left(CRD^{\pm}_{t,s,g}+\sum_{t=2}YCB^{\pm}_{t-1,s,g,op}CB^{\pm}_{t-1,s,g,op}\right)AF^{\pm}_{t,s,g}\geq\sum_{v=l}XDTE^{\pm}_{t,s,v} \quad (2.1.4f)$$

$$CRD^{\pm}_{t,s,o}+\sum_{t=2}YCB^{\pm}_{t-1,s,o,op}CB^{\pm}_{t-1,s,o,op}\leq T1^{\pm}_{t,s,o} \quad (2.1.4g)$$

$$T1^{\pm}_{t,s,o}\leq CRD^{\pm}_{t,s,o}+\sum_{t=2}YCB^{\pm}_{t-1,s,o,op}CB^{\pm}_{t-1,s,o,op}\leq T2^{\pm}_{t,s,o} \quad (2.1.4h)$$

$$CRD^{\pm}_{t,s,o}+\sum_{t=2}YCB^{\pm}_{t-1,s,o,op}CB^{\pm}_{t-1,s,o,op}\leq T3^{\pm}_{t,s,o} \quad (2.1.4i)$$

$$\left(CRD^{\pm}_{t,s,p}+\sum_{t=2}YCB^{\pm}_{t-1,s,p,op}CEB^{\pm}_{t-1,s,p,op}\right)AF^{\pm}_{t,s,p}\geq XE^{\pm}_{t,s,p} \quad (2.1.4j)$$

$$\left(CRD^{\pm}_{t,s,h}+\sum_{t=2}YCB^{\pm}_{t-1,s,h,op}CHB^{\pm}_{t-1,s,h,op}\right)AF^{\pm}_{t,s,h}\geq XH^{\pm}_{t,s,h} \quad (2.1.4k)$$

$$\left(CRD^{\pm}_{t,s,r}+\sum_{t=2}XCA^{\pm}_{t-1,s,r}\right)AF^{\pm}_{t,s,r}\geq XP^{\pm}_{t,s,r} \quad (2.1.4l)$$

$$\left(CRDE^{\pm}_{t,s,p}+\sum_{t=2}YCE^{\pm}_{t,s,p,op}CET^{\pm}_{t,s,p,op}\right)ATFE^{\pm}_{t,s,p}\geq XE^{\pm}_{t,s,p} \quad (2.1.4m)$$

$$\left(CRDE^{\pm}_{t,s,w}+\sum_{t=2}YCE^{\pm}_{t-1,s,w,op}CET^{\pm}_{t-1,s,w,op}\right)ATFE^{\pm}_{t,s,w}\geq XIE^{\pm}_{t,s,w} \quad (2.1.4n)$$

$$\left(CRDH^{\pm}_{t,s,h}+\sum_{t=2}YCH^{\pm}_{t,s,h,op}CHT^{\pm}_{t,s,h,op}\right)ATFH^{\pm}_{t,s,h}\geq XH^{\pm}_{t,s,h} \quad (2.1.4o)$$

$$\left(CRDH^{\pm}_{t,s,w}+\sum_{t=2}YCH^{\pm}_{t,s,w,op}CHT^{\pm}\right)ATFH^{\pm}_{t,s,w}\geq XIH^{\pm}_{t,s,w} \quad (2.1.4p)$$

$$\left(CRDH^{\pm}_{t,s,p}+\sum_{t=2}YCH^{\pm}_{t,s,p,op}CHT^{\pm}_{t,s,p,op}\right)ATFH^{\pm}_{t,s,p}\geq XE^{\pm}_{t,s,p}COH^{\pm}_{t,s,p,`h'} \quad (2.1.4q)$$

Emissions are modeled as the coefficients of activities for each technology. Their amounts are determined by each technology according to its emission efficiency. When the emission reduction is required, various technologies or energy alternatives with low-emission levels will be selected to replace those with higher-emission levels; this will lead to a significant increase of system cost. In addition, each emission amount will be limited with a target. The constraints that reflect such limitations can be formulated as follows:

$$\begin{aligned}&\sum_{s}\sum_{r}XP^{\pm}_{t,s,r}ENV^{\pm}_{t,s,r,q}+\sum_{s}\sum_{p}XE^{\pm}_{t,s,p}ENV^{\pm}_{t,s,p,q}\\&+\sum_{s}\sum_{h}XH^{\pm}_{t,s,h}ENV^{\pm}_{t,s,h,q}\\&+\sum_{s}\sum_{z}\sum_{y}\sum_{m}\sum_{n}XD^{\pm}_{t,s,z,y,m,n}ENV^{\pm}_{t,s,z,y,m,n,q}\\&+\sum_{s}\sum_{cz}\sum_{cy}\sum_{cm}\sum_{cn}XD^{\pm}_{t,s,cz,cy,cm,cn}ENV^{\pm}_{t,s,cz,cy,cm,cn,q}\\&-\sum_{s}\sum_{v}XDTI^{\pm}_{t,s,v}INP^{\pm}_{t,s,v,ee}ENV^{\pm}_{t,s,v,q}AVL^{\pm}_{t,s,v}\\&-\sum_{s}\sum_{u}XDTI^{\pm}_{t,s,u}INP^{\pm}_{t,s,u,ee}ENV^{\pm}_{t,s,u,q}AVK^{\pm}_{t,s,u}\\&-\sum_{s}\sum_{v}\sum_{o}XDTE^{\pm}_{t,s,v,o}INPR^{\pm}_{t,s,v,o,c,ee}ENV^{\pm}_{t,s,v,o,c,ee,q}AVL^{\pm}_{t,s,v,o}\\&-\sum_{s}\sum_{u}\sum_{o}XDTE^{\pm}_{t,s,u,o}INPR^{\pm}_{t,s,u,o,c,ee}ENV^{\pm}_{t,s,u,o,c,ee,q}AVL^{\pm}_{t,s,u,o}\\&\leq AENV^{\pm}_{t,q}\end{aligned} \quad (2.1.5)$$

The lower and upper bounds of energy availabilities are primarily due to the limited capacities of energy transportation and distribution. In addition, capacity expansions of technologies are also restricted by environmental, social, economic, technical and management conditions. In addition, all decision variables are considered to be positive, and those representing capacity-expansion options are restricted as either 0 or 1. The constraints reflecting these considerations can be formulated as follows:

$$XS^{\pm}_{t,s}\leq UB^{\pm}_{t,s} \quad (2.1.6a)$$

$$XS^{\pm}_{t,s}\geq LB^{\pm}_{t,s} \quad (2.1.6b)$$

$$XS^{\pm}_{t,s}\geq 0 \quad (2.1.6c)$$

$$0\leq YC^{\pm}_{t,s}\leq 1 \quad \text{and} \quad YC^{\pm}_{t,s}=\text{integer} \quad (4.3.6d)$$

$$CR_{t,s}\geq LB^{\pm}_{t,s} \quad (2.1.6e)$$

$$CR_{t,s}\leq UB^{\pm}_{t,s} \quad (2.1.6f)$$

$$ES_{t,s}\geq LB^{\pm}_{t,s} \quad (2.1.6g)$$

$$ES_{t,s}\leq UB^{\pm}_{t,s} \quad (2.1.6h)$$

2.2. Solution method

The developed DIP-CEM can be generalized into a mixed-integer interval-parameter linear programming problem as follows:

$$Min\ f^{\pm}=C^{\pm}X^{\pm} \quad (2.2.1a)$$

$$\text{s.t.}\quad A^{\pm}X^{\pm}\geq B^{\pm} \quad (2.2.1b)$$

$$X^{\pm}\geq 0 \quad (2.2.1c)$$

where

$$C^{\pm}=\{c^{\pm}_{j}=[c^{-}_{j},c^{+}_{j}]|\forall j\},\quad C^{\pm}\in\{\Re^{\pm}\}^{1\times n}$$

$$A^{\pm}=\{a^{\pm}_{ij}=[a^{-}_{ij},a^{+}_{ij}]|\forall i,j\},\quad A^{\pm}\in\{\Re^{\pm}\}^{m\times n}$$

$$B^{\pm} = \{b_i^{\pm} = [b_i^-, b_i^+] | \forall i\}, \quad B^{\pm} \in \{\Re^{\pm}\}^{m\times 1}$$

$$X^{\pm} = \{x_j^{\pm} = [x_j^-, x_j^+] | \forall j\}, \quad X^{\pm} \in \{\Re^{\pm}\}^{n\times 1}$$

Moreover, $x_j^{\pm}$ are continuous variables and $c_j^{\pm}$ are positive cost coefficients (when $j = 1, 2, \ldots, p_1$); $x_j^{\pm}$ are continuous variables and $c_j^{\pm}$ are negative cost coefficients (when $j = k_1 + 1, k_1 + 2, \ldots, k_1 + p_2$); $x_j^{\pm}$ are discrete variables and $c_j^{\pm}$ are positive cost coefficients (when $j = p_1 + 1,\ p_1 + 1,\ \ldots,\ k_1$); $x_j^{\pm}$ are discrete variables and $c_j^{\pm}$ are negative cost coefficients (when $j = k_1 + p_2 + 1,\ k_1 + p_2 + 2,\ \ldots,\ n$) ($p_1 \le k_1$, $p_2 \le k_2$, and $k_1 + k_2 + n$). According to Huang et al. [25], model (2.2.1) can be solved through a two-step method, where two sub-models (corresponding to f^- and f^+) are generated, respectively. The sub-model for f^- is first formulated and solved, and then the relevant sub-model f^+ can be formulated based on the generated lower bound solution.

The first sub-model corresponding to f^- can be developed as follows:

$$Min\ f^- = c_1^- x_1^- + c_2^- x_2^- + \cdots + c_{k_1}^- x_{k_1}^- + c_{k_1+1}^- x_{k_1+1}^+ + \cdots + c_n^- x_n^+ \tag{2.2.2a}$$

Subject to

$$a_{i1}^+ x_1^- + a_{i2}^+ x_2^- + \cdots + a_{ik_1}^+ x_{k_1}^- + a_{ik_1+1}^- x_{k_1+1}^+ + \cdots + a_{in}^- x_n^+ \ge b_i^-, \quad \forall i \tag{2.2.2b}$$

$x_j^{\pm}$ are continuous variables, $j = 1, 2, \ldots, p_1, k_1 + 1, k_1 + 2, \ldots, k_1 + p_2$, $x_j^{\pm}$ are discrete variables, $j = p_1 + 1,\ p_1 + 1,\ \ldots,\ k_1,\ k_1 + p_2 + 1,\ k_1 + p_2 + 2, \ldots, n$ ($p_1 \le k_1$, $p_2 \le k_2$, and $k_1 + k_2 = n$).

$$x_j^{\pm} \ge 0, \quad \forall j, \tag{2.2.2c}$$

According to Ref. [25], $x_{j,opt}^-$ ($j = 1, 2, \ldots, p_1$) represent continuous variables, $x_{j,opt}^-$ ($j = p_1 + 1,\ p_1 + 1,\ \ldots,\ k_1$) denote discrete ones; $x_{j,opt}^+$ ($j = k_1 + 1,\ k_1 + 2,\ \ldots,\ k_1 + p_2$) are for continuous variables, and $x_{j,opt}^+$ ($j = k_1 + p_2 + 1,\ k_1 + p_2 + 2,\ \ldots,\ n$) are for discrete ones. The $x_{j,opt}^-$ can be obtained from the solution corresponding to f^-. The solutions of decision variables can provide constraints for the second step of the solution process, which can be formulated as follows:

$$Min\ f^+ = c_1^+ x_1^+ + c_2^+ x_2^+ + \cdots + c_{k_1}^+ x_{k_1}^+ + c_{k_1+1}^+ x_{k_1+1}^- + \cdots + c_n^+ x_n^- \tag{2.2.3a}$$

Subject to

$$a_{i1}^- x_1^+ + a_{i2}^- x_2^+ + \cdots + a_{ik_1}^- x_{k_1}^+ + a_{ik_1+1}^+ x_{k_1+1}^- + \cdots + a_{in}^+ x_n^- \ge b_i^+, \quad \forall \tag{2.2.3b}$$

$x_j^{\pm}$ are continuous variables, $j = 1, 2, \ldots, p_1, k_1 + 1, k_1 + 2, \ldots, k_1 + p_2$, $x_j^{\pm}$ are discrete variables, $j = p_1 + 1,\ p_1 + 1,\ \ldots,\ k_1,\ k_1 + p_2 + 1,\ k_1 + p_2 + 2, \ldots, n$ ($p_1 \le k_1$, $p_2 \le k_2$, and $k_1 + k_2 = n$).

$$x_j^- \le x_{j,opt}^+, \quad j = 1, 2, \ldots, k_1, \tag{2.2.3c}$$

$$x_j^+ \ge x_{j,opt}^-, \quad j = k_1 + 1, k_1 + 2, \ldots, n \tag{2.2.3d}$$

$$x_j^{\pm} \ge 0, \quad \forall j. \tag{2.2.3e}$$

Each of sub-models (2.2.2) and (2.2.3) is an ordinary MILP problem with a single objective function. Thus, $f_{opt}^-, x_{j,opt}^-$ ($j = 1, 2, \ldots, p_1$), $x_{j,opt}^-$ ($j = p_1 + 1,\ p_1 + 1, \ldots, k_1$), $x_{j,opt}^+$ ($j = k_1 + 1,\ k_1 + 2,\ \ldots,\ k_1 + p_2$) and $x_{j,opt}^+$ ($j = k_1 + p_2 + 1,\ k_1 + p_2 + 2,\ \ldots,\ n$) can be obtained by solving sub-model (2.2.2), and $f_{opt}^+, x_{j,opt}^+$ ($j = 1, 2, \ldots, p_1$), $x_{j,opt}^+$ ($j = p_1 + 1,\ p_1 + 1,\ \ldots,\ k_1$), $x_{j,opt}^-$ ($j = k_1 + 1,\ k_1 + 2,\ \ldots,\ k_1 + p_2$) and $x_{j,opt}^-$ ($j = k_1 + p_2 + 1,\ k_1 + p_2 + 2, \ldots, n$) can be obtained by solving sub-model (2.2.3). Thus, we have $f_{opt}^{\pm} = [f_{opt}^-, f_{opt}^+]$, $f_{opt}^+ \ge f_{opt}^-$, $x_{j,opt}^{\pm} = [x_{j,opt}^-, x_{j,opt}^+]$, $x_{j,opt}^+ \ge x_{j,opt}^-$, $\forall j$. The solutions to the above MILP problems can be obtained through the existing commercial software. In general, the above algorithm can be summarized (in a pseudo-code format) as follows:

- Step 1: Formulate f^- sub-model.
- Step 2: Solve f^- sub-model to obtain $X_{j,opt}^-$ ($j = 1, 2, \ldots, k_1$) and $X_{j,opt}^+$ ($j = k_1 + 1, k_1 + 2, \ldots, n$).
- Step 3: Compute f_{opt}^-.
- Step 4: Formulate f^+ sub-model based on the solutions of $X_{j,opt}^-$ and $X_{j,opt}^+$ from f^-.
- Step 5: Solve f^+ sub-model to obtain $X_{j,opt}^+$ ($j = 1, 2, \ldots, k_1$) and $X_{j,opt}^-$ ($j = k_1 + 1, k_1 + 2, \ldots, n$).
- Step 6: Compute f_{opt}^+.
- Step 7: Return the optimal solutions of $X_{j,opt}^{\pm} = [X_{j,opt}^-, X_{j,opt}^+]$, $\forall j$ and $f_{opt}^{\pm} = [f_{opt}^-, f_{opt}^+]$.
- Step 8: End.

3. Application of DIP-CEM to the City of Waterloo, Canada

The City of Waterloo, located in the Regional Municipality of Kitchener-Waterloo, is a dynamic community with a strong socio-economic base. Taking 20,000 non-residential post-secondary students into consideration, the city's total population would be 113,100 in 2006 [26]. Spatially, it covers an area of only 64.1 km^2, leading to a population density of 1764.7 capita per km^2 [27]. The city's economy experienced an annual growth of 2.3% in 2006 [18]. The high population density and the relevant residential, commercial and transportational energy-related activities necessitate Waterloo's energy system to be effectively managed for dealing with issues of socio-economic development, GHG-emission reduction, transportation-mode shifting, city urbanization, and sustainable energy development.

3.1. Overview of the Waterloo energy system

The Waterloo energy system has limited fossil energy production and conversion activities. Gasoline, diesel and other downstream fuels are mostly imported. Electricity is primarily supplied by the Ontario power grid. The primary residential energy demands in the City include energy uses for space heating and cooling, water heating, residential lighting, and household-appliances functioning. Spacing cooling is fulfilled by room- and central-air conditioners [28]. The water-heating demands are mainly satisfied by electricity and natural-gas heating systems; the stock of the natural-gas heating systems is almost double that of electricity one. Electricity is the primary source for residential lighting. High efficiency CFBs (compact fluorescent bulbs) can be considered an option to reduce electricity demands. Household appliances, such as refrigerators, freezers, dishwashers, clothes washers, and dryers, as well as other home electronics, are mostly powered by electricity. Natural gas accounts for less than 5% of the total energy consumption by appliances in the city [28].

Based on building type, commercial energy demands in the community-scale energy system can be classified into schools, health-care facilities, offices, retail buildings, hotels/restaurants, and others. According to Ref. [28], space heating for commercial buildings is mainly offered by natural-gas heating systems. With respect to space cooling, a small number of central-air conditioners are powered by natural gas, while the majority of them are driven

by electricity. Water-heating demands are mostly satisfied by natural-gas water-heating systems. Indoor and street lighting are powered by electricity. Auxiliary equipment and motors pertaining to commercial activities also rely on electricity.

Waterloo no longer has regularly scheduled rail service. The transportation demand is satisfied by internal roads spreading to every corner of the community and external roads that connect Waterloo with Kitchener and Cambridge. Although the City covers a small region spatially, its dynamic residential and commercial activities necessitate a large number of passenger vehicles. It is indicated that more than 89% of employed labour force take passenger vehicles to their workplace and less than 4% of that choose public transit as their mode of transportation [28].

The study system has a time horizon of 25 years (from 1998 to 2022); the horizon is further divided into five periods, with each representing 5 years and being subdivided into winter (October to March) and summer (April to September) seasons. To facilitate the planning of Waterloo's energy system and GHG-emission reduction, one reference case (business-as-usual, BAU) and two scenarios are developed through DIP-CEM. In the reference case, the system is simulated in the absence of any particularly regulatory, economic or political barriers; all parameters and decision variables represent the existing and predicted socio-economic, technological and environmental conditions. Given a range of energy resources and technology alternatives, DIP-CEM opts to the use of the lowest-cost set of options to meet the pre-determined demands. The two scenarios are designed to assist the analysis of impacts of GHG-emission reduction on the energy system and to help identify the corresponding mitigation strategies. In scenario one, GHG emissions are assumed to be stabilized at the 2000 level in period 3 (2008–2012); in scenario two, the emissions are assumed to meet the Canada's target set in Kyoto Protocol (i.e. 94% of 1990 level by period 3).

Through literature review, expert survey and field investigation, the data describing the existing and predicted Waterloo energy system were collected, verified and calibrated. For instance, data of residential and commercial heating- and cooling-demands were primarily sourced from the Ministry of Ontario; those of transportation demands for goods and passengers were sourced from Transportation Canada. The information of the existing road capacity as well as the future road capacity expansions was partially based on the Mccormick Rankin Corporation research report [29]. The capacity-expansion options of heating and power generation facilities, as well as road and rail infrastructures, were considered integer variables. The uncertain inputs were expressed as intervals. Thus, the developed DIP-CEM was considered suitable to address the dynamics and uncertainties of the study system.

3.2. Result analysis

3.2.1. Energy systems planning under BAU condition

The solutions for imported and domestic energy supplies are shown in Table 1. It is indicated that natural gas, gasoline, and electricity would be dominant energy in the City of Waterloo. Among them, natural gas would be the largest in the winter. Contrast to the supplies of natural gas, gasoline and electricity, those of diesel, heating oil and propane would be insignificant. Among them, the supply of diesel in the winter would be approximated to that of heating oil, and much more than that of propane. Similar to gasoline and electricity supplies, diesel supply in the summer would approximately equal to that in the winter. The seasonal dispatches of natural gas, heating oil and propane supplies would be attributed to their economic and technical advantages in meeting residential and commercial space heating demands in the winter.

Table 1 shows variations of annual natural-gas supply. It is demonstrated that significant increase would be emerged in period 2, when natural-gas supply has a net increment of [1.194, 1.367] PJ in period 1. In the consequent periods (periods 2–5), the supply would rise steadily, corresponding to the growing residential and commercial energy demands for space heating in the winter. It is also shown in Table 1 that gasoline supply would be [1.994, 2.505], [2.119, 2.666], [2.252, 2.838], [2.399, 3.068] and [2.584, 3.292] PJ in the winter of periods 1 to 5, respectively; diesel supply would be [0.395, 0.488], [0.424, 0.524], [0.454, 0.562], [0.488, 0.609] and [0.547, 0.679] PJ in the winter of periods 1 to 5, respectively. Gasoline is consumed mostly by passenger vehicles; diesel is consumed by freight ones. The gasoline and diesel supplies in the summer would be greater than those in the winter. In periods 1–5, the electricity demands, both in the winter and the summer, would rise continuously. Electricity would be the primary energy in meeting the demands for lighting, residential appliances, and commercial equipment and motors, as well as space cooling; heating oil and propane would mostly contribute to space heating in the winter. Heating oil supply would stabilize at the level of [0.486, 0.534] PJ from periods 2–5; propane supply would decline from an interval of [0.106, 0.113] PJ in period 2 to deterministic value of 0.096 PJ in period 5. In the summer, both fuels would fail in competing with natural gas for water heating.

Energy demands for space heating would account for the primary residential demands in the City of Waterloo, since the community climate conditions have the characteristic of long heating degree days. Table 2 contains the solutions for heating provided by various technologies in 5 periods. In period 1 (years 1998–2002), the demands for new detached houses, attached

Table 1
Annual energy supplies (PJ).

	Season	1	2	3	4	5
Natural gas	Winter	[6.464, 7.110]	[7.658, 8.477]	[8.299, 9.249]	[8.974, 10.019]	[9.625, 10.740]
	Summer	[0.567, 0.624]	[0.615, 0.677]	[0.622, 0.684]	[0.630, 0.693]	[0.638, 0.701]
Gasoline	Winter	[1.994, 2.505]	[2.119, 2.666]	[2.252, 2.838]	[2.399, 3.068]	[2.584, 3.292]
	Summer	[2.014, 2.531]	[2.143, 2.695]	[2.279, 2.872]	[2.435, 3.113]	[2.624, 3.342]
Diesel	Winter	[0.395, 0.488]	[0.424, 0.524]	[0.454, 0.562]	[0.488, 0.609]	[0.547, 0.679]
	Summer	[0.397, 0.491]	[0.426, 0.527]	[0.457, 0.565]	[0.509, 0.634]	[0.551, 0.685]
Electricity	Winter	[1.258, 1.385]	[1.370, 1.508]	[1.484, 1.615]	[1.604, 1.749]	[1.780, 1.946]
	Summer	[1.289, 1.426]	[1.414, 1.566]	[1.561, 1.727]	[1.720, 1.902]	[1.881, 2.080]
Heating oil	Winter	[0.439, 0.483]	[0.486, 0.534]	[0.486, 0.534]	[0.486, 0.534]	[0.486, 0.534]
	Summer	0	0	0	0	0
Propane	Winter	[0.097, 0.107]	[0.106, 0.113]	[0.106, 0.107]	[0.096, 0.096]	[0.096, 0.096]
	Summer	0	0	0	0	0

Table 2
Space heating for new residential demands (PJ).

	Season	1	2	3	4	5
New detached house (natural gas medium)[a]	Winter	0	[0.075, 0.090]	[0.129, 0.155]	[0.185, 0.222]	[0.247, 0.296]
	Summer	0	0	0	0	0
New attached house (natural gas medium)[b]	Winter	0	[0.037, 0.045]	[0.065, 0.078]	[0.092, 0.111]	[0.123, 0.148]
	Summer	0	0	0	0	0
New apartment (natural gas medium)[c]	Winter	0	[0.262, 0.314]	[0.452, 0.543]	[0.646, 0.775]	[0.863, 1.035]
	Summer	0	0	0	0	0
Total demand	Winter	0	[0.374, 0.449]	[0.646, 0.775]	[0.923, 1.108]	[1.233, 1.479]
	Summer	0	0	0	0	0

[a] New detached house with medium-efficiency natural-gas heating technology.
[b] New attached house with medium-efficiency natural-gas heating technology.
[c] New apartment with medium-efficiency natural-gas heating technology.

houses and apartments would be zero. In periods 2 to 5, the new detached houses would account for [0.075, 0.090], [0.129, 0.155], [0.185, 0.222] and [0.247, 0.296] PJ, respectively; the new attached houses would contribute [0.037, 0.045], [0.065, 0.078], [0.092, 0.111] and [0.123, 0.148] PJ, respectively; the new apartments would take [0.262, 0.314], [0.452, 0.543], [0.646, 0.775] and [0.863, 1.035] PJ, respectively. Total demands for space heating in these new residential buildings would be [0.374, 0.449], [0.646, 0.775], [0.923, 1.108] and [1.233, 1.479] PJ in periods 2 to 5, respectively. It is indicated that natural-gas heating system with medium efficiency (NG-medium) would be successful in a competition with other technologies for space heating in all three types of buildings.

Table 3 shows the solution of energy consumption by residential sector (space heating, cooling, lighting, appliances and water heating). Natural gas and electricity consumptions in the winter would increase, primarily corresponding to socio-economic development in the Waterloo community. Heating oil and propane would be inferior to electricity and natural gas in terms of fuel cost and technology performance, this would result in stable or declining trends of their consumption in periods 2–5. Among all the fuels consumed in meeting residential energy demands, natural gas would rank the first position, being far greater than total contributions of other energy resources. Electricity would occupy the second position, used mostly by electric-baseboard-heating, water-heating and lighting systems. Heating oil and propane would be considered supplementary fuels for space heating, with a small amount consumed. In the summer, natural gas would be used mostly for water heating. Electricity would be used mostly for space cooling and lighting. With respect to heating oil and propane, their summer consumption would be zero, due to their higher overall cost than natural gas.

Table 4 demonstrates the energy consumption portfolio of commercial sector designed through the DIP-CEM. The winter consumption of natural gas would rise from [2.438, 2.681] PJ in period 1 to [3.300, 3.609] PJ in period 5; that of electricity would increase from [0.585, 0.644] PJ in period 1 to [0.790, 0.873] PJ in period 5; that of heating oil would be [0.197, 0.216] PJ in period 1 and [0.275, 0.303] PJ from period 2 onwards; that of propane would contribute around 0.07 PJ in all five periods. In general, the consumption of heating oil and propane would remain at a low

Table 3
Residential energy consumption (PJ).

	Season	1	2	3	4	5
Natural gas	Winter	[4.026, 4.429]	[5.049, 5.604]	[5.481, 6.112]	[5.921, 6.625]	[6.403, 7.189]
	Summer	[0.473, 0.521]	[0.515, 0.567]	[0.515, 0.567]	[0.515, 0.567]	[0.515, 0.567]
Electricity	Winter	[0.671, 0.738]	[0.735, 0.809]	[0.799, 0.880]	[0.864, 0.951]	[0.937, 1.032]
	Summer	[0.562, 0.626]	[0.630, 0.704]	[0.715, 0.798]	[0.807, 0.900]	[0.910, 1.013]
Heating oil	Winter	[0.242, 0.267]	[0.275, 0.303]	[0.275, 0.303]	[0.275, 0.303]	[0.275, 0.303]
	Summer	0	0	0	0	0
Propane	Winter	[0.031, 0.034]	[0.035, 0.038]	0.035	0.035	0.035
	Summer	0	0	0	0	0

Table 4
Commercial energy consumption (PJ).

	Season	1	2	3	4	5
Natural gas	Winter	[2.438, 2.681]	[2.608, 2.869]	[2.818, 3.110]	[3.098, 3.410]	[3.300, 3.609]
	Summer	[0.093, 0.103]	[0.100, 0.110]	[0.107, 0.117]	[0.114, 0.126]	[0.122, 0.134]
Electricity	Winter	[0.585, 0.644]	[0.633, 0.696]	[0.682, 0.750]	[0.708, 0.784]	[0.790, 0.873]
	Summer	[0.724, 0.797]	[0.787, 0.860]	[0.843, 0.927]	[0.910, 1.001]	[0.968, 1.064]
Heating oil	Winter	[0.197, 0.216]	[0.211, 0.232]	[0.211, 0.232]	[0.211, 0.232]	[0.211, 0.232]
	Summer	0	0	0	0	0
Propane	Winter	[0.066, 0.073]	[0.071, 0.078]	0.071	0.061	[0.061, 0.078]
	Summer	0	0	0	0	0

Table 5
Transportational energy consumptions (PJ).

	Season	1	2	3	4	5
Gasoline	Winter	[1.994, 2.505]	[2.119, 2.666]	[2.252, 2.838]	[2.399, 3.068]	[2.584, 3.292]
	Summer	[2.014, 2.531]	[2.143, 2.695]	[2.279, 2.872]	[2.435, 3.113]	[2.624, 3.342]
Diesel	Winter	[0.395, 0.488]	[0.424, 0.524]	[0.454, 0.562]	[0.488, 0.609]	[0.547, 0.679]
	Summer	[0.397, 0.491]	[0.426, 0.527]	[0.457, 0.565]	[0.509, 0.634]	[0.551, 0.685]
Electricity	Winter	0	0	0	0	0
	Summer	0	0	0	0	0

level. Natural-gas consumption would account for the largest contribution among all energy resources. Electricity would be identified as the second contributor. Its consumption in the summer would be greater than that in the winter. This variation is mainly due to raised electricity demands by central- or room-air conditioners for space cooling in offices, retail outlets, schools and other commercial buildings. Natural gas would primarily be used to provide heated water in the summer. Heating oil and propane would not be considered in the summer.

Generally, gasoline and diesel are dominant fuels for running vehicles, although a number of innovative technologies have been developed to use alternative fuel, such as hybrid fuel, hydrogen, and solar power. This is also true for the City of Waterloo, where vehicles using unconventional fuel can be neglected in comparison with that running on traditional fuels (gasoline and diesel). This fact is reflected by the solutions obtained through the DIP-CEM (Table 5). It is shown that gasoline or diesel consumption in the winter would be slightly lower than that in summer. This is partially due to higher amount of transportation demands in the summer than in the winter. The seasonal variation of diesel is more significant than that of gasoline.

The solutions for road provision and capacity expansion are given in Table 6. There are three major roads linking Waterloo with Kitchener and Cambridge, represented by Roads 7, 9a and 11, respectively. To achieve the objective of least system cost, Road 7 would carry 1.671 million vehicles (passenger car equivalent) in the NB (north bound)/EB (east bound) direction in the winter or the summer of periods 1 and 2. From periods 3 onwards, it could take [1.820, 2.280], 2.81, and 3.441 million vehicles in the winter and [1.850, 2.322], [2.909, 2.938] and [3.529, 3.529] million vehicles (passenger car equivalent) in the summer. Road 9a would take [1.243, 1.560] 1.87, 1.87, 2.22 and 2.22 in the NB/EB direction in the winter of periods 1 to 5, respectively. It would take the same amount of vehicles in the summer, except in period 1 when [1.267, 1.587] million vehicles (passenger car equivalent) would be conveyed. Road 11 would transport 2.037, [2.431, 2.813], 3.52, 3.52 and 4.40 million vehicles (passenger car equivalent) in the NB/EB direction in the winter of periods 1 to 5, respectively. There would have slight difference in the number of vehicles delivered between the summer and the winter occurring in period 2 ([2.458, 2.843] million vehicles). It is indicated that, with the increasing traffic volume, each road would reach its maximum allowed

Table 6
Unitization and expansion of roads and light trains (million cars equivalent).

	Season	1	2	3	4	5
Road 7-NB/EB	Winter	1.671	1.671	[1.820, 2.280]	2.81	3.441
	Summer	1.671	1.671	[1.850, 2.322]	[2.909, 2.938]	3.529
Road 9a-NB/EB	Winter	[1.243, 1.560]	1.87	1.87	2.22	2.22
	Summer	[1.267, 1.587]	1.87	1.87	2.22	2.22
Road 11-NB/EB	Winter	2.037	[2.431, 2.813]	3.52	3.52	4.40
	Summer	2.037	[2.458, 2.843]	3.52	3.52	4.40
New road-NB/EB	Winter	0	0	0	[0, 1.9]	[0, 1.9]
	Summer	0	0	0	[0, 1.9]	[0, 1.9]
Road 7-SB/WB	Winter	1.424	1.424	1.424	1.424	[1.279, 1.395]
	Summer	1.424	1.424	1.424	1.424	[1.226, 1.568]
Road 9a-SB/WB	Winter	[1.371, 1.590]	1.59	1.59	1.59	1.59
	Summer	[1.395, 1.590]	1.59	1.59	1.59	1.59
Road 11-SB/WB	Winter	[0.783, 0.796]	[1.043, 1.347]	[1.589, 1.982]	[2.052, 2.361]	[2.651, 2.992]
	Summer	[0.783, 0.823]	[1.070, 1.377]	[1.619, 2.014]	[2.150, 2.487]	[2.738, 2.992]
New road-SB/WB	Winter	0	0	0	[0, 0.95]	[0, 0.95]
	Summer	0	0	0	[0, 0.95]	[0, 0.95]
Road 7-bus	Winter	0.007	0.007	0.007	0.007	0.016
	Summer	0.007	0.007	0.007	0.007	0.016
Road 9a-bus	Winter	0.007	0.007	0.007	0.016	0.016
	Summer	0.007	0.007	0.007	0.016	0.016
Road 11-bus	Winter	0.007	0.007	0.007	0.007	0.016
	Summer	0.007	0.007	0.007	0.007	0.016
New road-bus	Winter	0	0	0	0	[0, 0.010]
	Summer	0	0	0	0	[0, 0.010]

operating capacity eventually (Road 9a, then Road 11, followed by Road 7). After that, the vehicle would run at a reduced speed. Finally, road carrying capacity needs to be expanded. Such expansion would be brought a new road into use in period 4. The new road would be built along the corridor in Waterloo's downtown area. It would take [0, 1.9] million vehicles in the NB/EB direction in both the summer and the winter of periods 4 and 5.

In the SB (south bound)/WB (west bound) direction, since the traffic volume is lower than that in the NB/EB direction, the existing roads would never reach their maximum operating capacity. However, the new road (constructed to relieve the traffic load in the NB/EB direction) would still dilute the traffic volume by an amount of [0, 0.95] million vehicles (passenger car equivalent).

The solution obtained through DIP-CEM indicates that the public transportation vehicles would be limited to buses. Table 6 shows that, when roads work at their maximum operating capacity due to increasing transportation demands, additional bus service would be required to carry people who are willing to take a public transit. In detail, there would be a desire for more buses on Road 9a in period 4, and Roads 7 and 11 in period 5. New bus service would be initiated on new road in period 5.

Table 7 presents the solutions for GHG emissions by sources. GHG emission generated in the winter would be approximately three times that generated in the summer of each period. This is mainly due to the combustion of natural gas, heating oil and propane for space heating in the winter. Accordingly, the difference of residential and commercial sectors' GHG emissions between the summer and the winter would be more significant than that of total GHG emissions. For instance, the GHG emissions of residential sector would be [221.66, 243.83], and [343.27, 384.60] ktonnes in the winter of periods 1 and 5, respectively; that would only have [23.66, 26.06] and [25.77, 28.35] ktonnes in the summer of periods 1 and 5, respectively. With respect to GHG emissions of transportational sector, the seasonal variation is insignificant. The winter amount would rise from [167.23, 209.56] ktonnes in period 1 to [219.16, 270.93] ktonnes in period 5; the summer amount would increase from [168.80, 211.51] ktonnes in period 1 to [222.25, 274.69] ktonnes in period 5. The primary GHG emissions associated with energy-related activities in the winter would be contributed mostly by residential sector and then by transportation; those in the summer would be attributed mostly to the transportation sector.

3.2.2. Energy systems planning under GHG-emission reduction scenarios

The Kyoto Protocol has been established under the United Nations Framework Convention on Climate Change (UNFCCC) to set initial targets for reducing GHG emissions [30]. Under the Kyoto Protocol, Canada is required to reduce its GHG emissions to 94% of the 1990 level. Under the BAU case, annual GHG emissions in the City of Waterloo would reach [0.871, 1.021] million tonnes by period 3 (period of 2008–2012) and [1.002, 1.169] million tonnes by period 5 (2018–2022). This target can be achieved in many different ways, each with its own actions, costs and consequences. Regardless of whatever option that is selected, the model has to satisfy both the least-cost objective and the Kyoto-emission cap. Thus residential, commercial and transportational energy-related activities would be significantly affected, and their contributions to emission reduction would vary according to their adaptation capability and capacity.

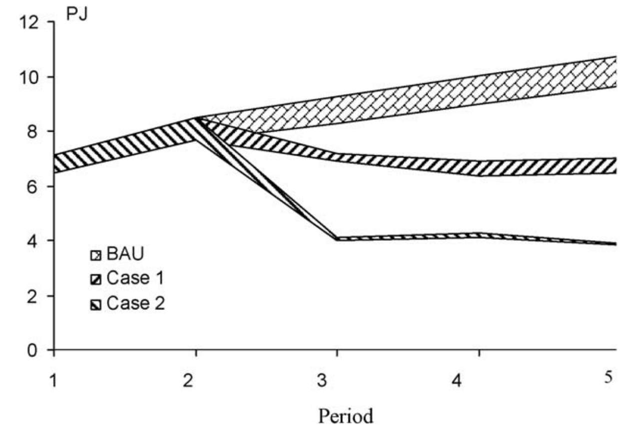

Fig. 2. Natural-gas supplies by cases in the winter.

Under GHG-reduction constraints, from period 3 onwards, the annual natural-gas supply would be significantly reduced. In the winter of period 3, the natural-gas supply would be respectively [6.926, 7.158] and [4.026, 4.087] PJ in cases (or scenarios) one and two, respectively, being far less than that in the BAU case; in the winter of period 5, it would be further reduced to [6.478, 6.990] and [3.845, 3.902] PJ in cases one and two, respectively (Fig. 2). In the summer, the natural-gas supply would even become zero, with the exception of [0.008, 0. 009] PJ allowed in period 5 in case one. This variation indicates that the direct impact of GHG-emission reduction would necessitate low-efficiency natural-gas technologies for space heating and water heating to be partially replaced by high-efficiency ones. Contrast to the GHG-emission reduction impacts on natural-gas supply, those on gasoline and diesel supplies would be insignificant until period 5 in case one and period 4 in case two. This is due to the high system costs of vehicles with alternative fuel (e.g. hybrid car) and the road-capacity expansion with new transit vehicles (e.g. light train). With respect to electricity, the winter supply in period 3 would rise from [1.484, 1.615] PJ in BAU case to [2.050, 2.389] PJ and [3.837, 4.481] PJ in cases one and two, respectively (Fig. 3). The summer supply in period 3 would also grow to [1.755, 1.938] and [1.754, 1.936] PJ in cases one and two, respectively, from [1.561, 1.727] PJ in BAU case.

Table 7
Annual greenhouse-gas emissions (ktonnes).

	Season	1	2	3	4	5
Residential	Winter	[221.66, 243.83]	[275.66, 305.66]	[297.15, 330.75]	[319.15, 356.40]	[343.27, 384.60]
	Summer	[23.66, 26.06]	[25.77, 28.35]	[25.77, 28.35]	[25.77, 28.35]	[25.77, 28.35]
Commercial	Winter	[141.26, 155.39]	[151.15, 166.27]	[161.62, 177.80]	[175.01, 192.16]	[185.11, 203.27]
	Summer	[4.66, 5.13]	[4.99, 5.49]	[5.34, 5.87]	[5.71, 6.28]	[6.11, 6.72]
Transportation	Winter	[167.23, 209.56]	[178.03, 223.27]	[189.14, 237.98]	[202.09, 250.69]	[219.16, 270.93]
	Summer	[168.80, 211.51]	[179.85, 225.53]	[191.55, 240.59]	[206.08, 255.57]	[222.25, 274.69]
Total GHG	Winter	[530.15, 608.77]	[604.74, 695.10]	[648.20, 746.53]	[696.26, 799.25]	[747.54, 858.80]
	Summer	[197.12, 242.70]	[210.61, 259.36]	[222.66, 274.81]	[237.56, 290.19]	[254.13, 309.76]

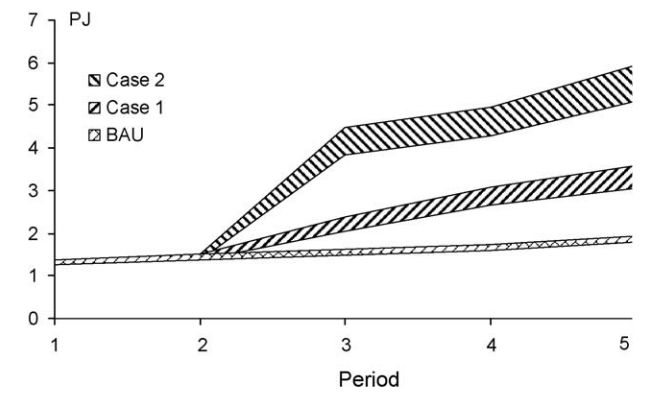

Fig. 3. Electricity supplies by cases in the winter.

Such an increment of electricity supply would be in accordance with the requirement for replacing high-emission technologies with low-emission ones, and the assumption that emissions associated with electricity generation are attributed to the region where the generation plants are located. As for heating oil and propane, their summer consumption would be totally phased out in cases one and two; about 0.115 PJ of heating oil and [0.061, 0.073] PJ of propane would be provided by high-efficiency technology for the winter space heating in case one in period 5.

The solutions in Table 8 provide further analysis of the impacts of GHG-emission reduction on the residential sector. It shows that the winter natural-gas consumption in period 3 would be reduced from [5.481, 6.112] PJ in BAU case to [3.992, 4.231] and [1.462, 1.521] PJ in cases one and two, respectively; the consumption would be further reduced in period 5. The winter consumptions of heating oil and propane would be cut to zero due to their relatively higher costs and emissions than natural gas and electricity. Regarding the electricity, its winter consumption in period 3 would be increased to [1.365, 1.635] PJ in case one and further to [2.857, 3.241] PJ in case two. In period 5, it would soar to [2.261, 2.692] and [3.767, 4.299] PJ in cases one and two, respectively. Most of these increments would help fill the gap caused by reducing the utilization of natural gas, heating oil and propane.

Table 9 contains the solutions for energy consumption by commercial sector under BAU conditions and the GHG-emission reduction prerequisites. In comparison with the winter natural-gas consumption in BAU case, that in case one would increase slightly in periods 3 and 4, and decline insignificantly in period 5; that in case two would decrease from period 3 onwards. The variation in case one is mainly due to the phasing out of heating oil and propane for space heating; the decrease in case two indicates that natural gas would also be reduced when more GHG emissions needs to be trimmed. Without the opportunity to replace heating oil and propane for water heating in the summer, the summer consumption of natural gas in both cases would decline to zero in periods 3 and 4. Corresponding to the increase of winter natural-gas consumption in case one in period 3, there would be no additional electricity required for space heating. However, in case one in period 4 and in case two in periods 3–5, electricity would become economically feasible for providing heating when natural gas alone could hardly meet the GHG-emission reduction target.

When GHG emissions are required to be mitigated voluntarily in the City of Waterloo, it would be economically unfeasible for the transportation sector to contribute significantly to the task (case one). When GHG emissions are required to be stabilized at the 2000 level (case one) in period 4, the transportation sector would still be inactive. However, to meet the Kyoto target (case two), a new trail would be built to convey 32 kilo shifts light trains seasonally for commuting people in and out of Waterloo. In period

Table 8
Residential energy consumptions (PJ).

	Season	1	2	3	4	5
Natural gas-BAU	Winter	[4.026, 4.429]	[5.049, 5.604]	[5.481, 6.112]	[5.921, 6.625]	[6.403, 7.189]
	Summer	[0.473, 0.521]	[0.515, 0.567]	[0.515, 0.567]	[0.515, 0.567]	[0.515, 0.567]
Natural gas-Case 1	Winter	[4.003, 4.404]	[4.991, 5.525]	[3.992, 4.231]	[3.247, 3.508]	[3.351, 3.569]
	Summer	[0.473, 0.521]	[0.515, 0.567]	0	0	0
Natural gas-Case 2	Winter	[3.979, 4.377]	[4.953, 5.496]	[1.462, 1.521]	[1.534, 1.592]	[1.231, 1.286]
	Summer	[0.473, 0.521]	[0.515, 0.567]	0	0	0
Electricity-BAU	Winter	[0.671, 0.738]	[0.735, 0.809]	[0.799, 0.880]	[0.864, 0.951]	[0.937, 1.032]
	Summer	[0.562, 0.626]	[0.630, 0.704]	[0.715, 0.798]	[0.807, 0.900]	[0.910, 1.013]
Electricity-Case 1	Winter	[0.671, 0.738]	[0.735, 0.809]	[1.365, 1.635]	[1.939, 2.263]	[2.261, 2.692]
	Summer	[0.562, 0.626]	[0.630, 0.704]	[0.910, 1.012]	[1.002, 1.114]	[1.106, 1.228]
Electricity-Case 2	Winter	[0.671, 0.738]	[0.735, 0.809]	[2.857, 3.241]	[3.142, 3.575]	[3.767, 4.299]
	Summer	[0.562, 0.626]	[0.630, 0.704]	[0.908, 1.011]	[1.001, 1.112]	[1.104, 1.226]
Heating oil-BAU	Winter	[0.242, 0.267]	[0.275, 0.303]	[0.275, 0.303]	[0.275, 0.303]	[0.275, 0.303]
	Summer	0	0	0	0	0
Heating oil-Case 1	Winter	[0.269, 0.296]	[0.314, 0.355]	0	0	0
	Summer	0	0	0	0	0
Heating oil-Case 2	Winter	[0.297, 0.326]	[0.356, 0.391]	0	0	0
	Summer	0	0	0	0	0
Propane-BAU	Winter	[0.031, 0.034]	[0.035, 0.038]	0.035	0.035	0.035
	Summer	0	0	0	0	0
Propane-Case 1	Winter	[0.031, 0.034]	[0.035, 0.038]	0	0	0
	Summer	0	0	0	0	0
Propane-Case 2	Winter	[0.031, 0.034]	[0.035, 0.038]	0	0	0
	Summer	0	0	0	0	0

Table 9
Commercial energy consumptions (PJ).

	Season	1	2	3	4	5
Natural gas-BAU	Winter	[2.438, 2.681]	[2.608, 2.869]	[2.818, 3.110]	[3.098, 3.410]	[3.300, 3.609]
	Summer	[0.093, 0.103]	[0.100, 0.110]	[0.107, 0.117]	[0.114, 0.126]	[0.122, 0.134]
Natural gas-Case 1	Winter	[2.438, 2.681]	[2.608, 2.869]	[2.933, 3.227]	[3.108, 3.397]	[3.127, 3.421]
	Summer	[0.093, 0.103]	[0.100, 0.110]	0	0	[0.008, 0.009]
Natural gas-Case 2	Winter	[2.438, 2.681]	[2.608, 2.869]	[2.564, 2.567]	[2.590, 2.663]	[2.614, 2.616]
	Summer	[0.093, 0.103]	[0.100, 0.110]	0	0	0
Electricity-BAU	Winter	[0.585, 0.644]	[0.633, 0.696]	[0.682, 0.750]	[0.708, 0.784]	[0.790, 0.873]
	Summer	[0.724, 0.797]	[0.787, 0.860]	[0.843, 0.927]	[0.910, 1.001]	[0.968, 1.064]
Electricity-Case 1	Winter	[0.585, 0.644]	[0.633, 0.696]	[0.682, 0.750]	[0.732, 0.823]	[0.790, 0.887]
	Summer	[0.724, 0.792]	[0.781, 0.854]	[0.842, 0.922]	[0.909, 0.994]	[0.966, 1.056]
Electricity-Case 2	Winter	[0.585, 0.644]	[0.633, 0.696]	[0.978, 1.236]	[1.147, 1.379]	[1.338, 1.637]
	Summer	[0.724, 0.792]	[0.781, 0.854]	[0.842, 0.922]	[0.909, 0.994]	[0.973, 1.063]
Heating oil-BAU	Winter	[0.197, 0.216]	[0.211, 0.232]	[0.211, 0.232]	[0.211, 0.232]	[0.211, 0.232]
	Summer	0	0	0	0	0
Heating oil-Case 1	Winter	[0.197, 0.216]	[0.211, 0.232]	0	0	[0.115, 0.115]
	Summer	0	0	0	0	0
Heating oil-Case 2	Winter	[0.197, 0.216]	[0.211, 0.232]	0	0	0
	Summer	0	0	0	0	0
Propane-BAU	Winter	[0.066, 0.073]	[0.071, 0.078]	0.071	0.061	[0.061, 0.078]
	Summer	0	0	0	0	0
Propane-Case 1	Winter	[0.066, 0.073]	[0.071, 0.078]	0	0	[0.061, 0.073]
	Summer	0	0	0	0	0
Propane-Case 2	Winter	[0.066, 0.073]	[0.071, 0.078]	0	0	0
	Summer	0	0	0	0	0

5, a level of 44 kilo shifts of light trains would be operated under both cases one and two, corresponding to the reduction of GHG emission by transportation sector (Fig. 4).

Consequently, as many people would be transported by light trains, the road expansion would be unnecessary and the average vehicle speed on Roads 7, 9a and 11 would increase corresponding to the reduced traffic volume (Table 10). Trains would be operated in both cases one and two during period 5. Correspondingly, in the NB/EB direction, Road 7 would only carry 1.671 million vehicles in the NB/EB direction; Road 9a would take 0.448 million vehicles; Road 11 would only serve 2.037 million vehicles (passenger car equivalent) in the winter or summer in period 5. The traffic volume in the SB/WB direction would also decrease more or less corresponding to the service of light train.

The above analysis indicates that the adaptation to GHG-emission reduction of transportational sector would rely on changes in the transit mode. Such an adaptation to GHG-emission reduction would have direct and indirect impacts on energy consumptions by the transportational sector. Corresponding to

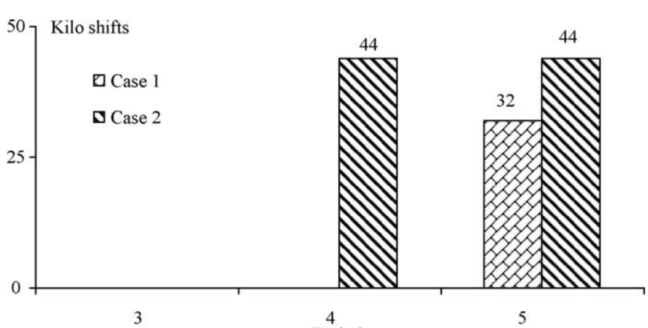

Fig. 4. Facility expansion and utilization of light train.

the adaptation strategies generated through the DIP-CEM, in case two of period 4, gasoline consumption would be reduced to [2.194, 2.751] and [2.224, 2.788] PJ in winter and summer, respectively; diesel consumption would decline to [0.467, 0.576] and [0.488, 0.601] PJ in winter and summer, respectively (Table 11). In period 5, gasoline and diesel vehicles and electricity powered light trains would work cooperatively to meet the growing transportation demands and help stabilize the GHG-emission reduction targets.

Although GHG emissions from residential, commercial and transportational sectors vary significantly, their contributions to GHG-emission reduction may not be commensurate with their generation. Table 12 contains the solutions of GHG-emission reduction in different sectors. From periods 3 onwards, when GHG emission is required to be stabilized to the 2000 level (case one) or 96% of the 1990 level (case two), the residential sector would always be the largest contributor in accomplishing such a task. The summer would see its GHG emission becoming zero in both reduction cases from periods 3 onwards. The summer contributions of the commercial sector would decline to zero in both cases (periods 3 and 4) and case two (period 5), an emission level of [0.40, 0.44] ktonnes would still be allowed in case one (period 5). In comparison with residential and commercial sectors, the transportation sector would be reluctant to take the commitment until the case two in period 4. In period 5, the transportational sector would help the residential and commercial sectors achieve GHG-emission reduction task in both cases. It is indicated that there would be more cost-effective low-emission technologies and energy alternatives for dealing with GHG-emission reduction by the residential and commercial sectors than by the transportation sector.

Through the above analysis, it is indicated that reducing GHG emissions would call for low-emission technologies to replace high-emission ones. However, these low-emission technologies

Table 10
Unitization and expansion of roads and light trains (million cars equivalent).

	Season	1	2	3	4	5
Road 7-NB/EB-BAU	Winter	1.671	1.671	[1.820, 2.280]	2.81	3.441
	Summer	1.671	1.671	[1.850, 2.322]	[2.909, 2.938]	[3.529, 3.529]
Road 7-NB/EB-Case 1	Winter	1.671	1.671	[1.820, 2.280]	2.81	1.671
	Summer	1.671	1.671	[1.850, 2.312]	2.909	1.671
Road 7-NB/EB-Case 2	Winter	1.671	1.671	[1.820, 2.280]	1.671	1.671
	Summer	1.671	1.671	[1.850, 2.312]	1.671	1.671
Road 9a-NB/EB-BAU	Winter	[1.243, 1.560]	1.870	1.870	2.221	2.221
	Summer	[1.267, 1.587]	1.870	1.870	2.221	2.221
Road 9a-NB/EB-Case 1	Winter	[1.243, 1.560]	1.870	1.870	2.221	0.448
	Summer	[1.267, 1.587]	1.870	1.870	2.221	0.448
Road 9a-NB/EB-Case 2	Winter	[1.243, 1.560]	1.870	1.870	0.448	0.448
	Summer	[1.267, 1.587]	1.870	1.870	0.448	0.448
Road 11-NB/EB-BAU	Winter	2.037	[2.431, 2.813]	3.52	3.52	4.40
	Summer	2.037	[2.458, 2.843]	3.52	3.52	4.40
Road 11-NB/EB-Case 1	Winter	2.037	[2.431, 2.813]	3.52	3.52	2.037
	Summer	2.037	[2.458, 2.843]	3.52	3.52	2.037
Road 11-NB/EB-Case 2	Winter	2.037	[2.431, 2.813]	3.52	2.037	2.037
	Summer	2.037	[2.458, 2.843]	3.52	2.037	2.037
New road-NB/EB-BAU	Winter	0	0	0	[0, 1.9]	[0, 1.9]
	Summer	0	0	0	[0, 1.9]	[0, 1.9]
New road-NB/EB-Case 1	Winter	0	0	0	0	0
	Summer	0	0	0	0	0
New road-NB/EB-Case 2	Winter	0	0	0	0	0
	Summer	0	0	0	0	0

are often at a higher cost than the high-emission ones. Hence, the more the GHG emissions are reduced, the higher the system cost occurs. Obviously, there is a tradeoff between environmental and economic goals. This tradeoff can be effectively analyzed through the developed DIP-CEM (Figs. 5 and 6). Under the BAU condition, corresponding to the lowest system costs, the GHG emission would be at the highest level; the highest total system costs in case two is associated with the lowest GHG emissions; the middle-level system costs corresponds to middle-level GHG emissions.

3.3. Discussions

The solutions of DIP-CEM for the City of Waterloo under BAU condition and GHG-emission reduction cases were presented in Tables 1–12 and Figs. 2–6. The BAU study (Tables 1–7) provided a guideline for planning and managing Waterloo's energy system under a social and economic development scenario. It also proposed a cost-effective approach for supporting decisions of energy development and road-capacity expansion. The analysis of GHG-emission reduction cases (Tables 8–12 and Figs. 2–6) helped design the least-cost energy portfolio for the community in meeting the Kyoto protocol. The proposed portfolio can further support policy formulation in dealing with GHG-emission reduction issues. In addition, the analysis of tradeoff between economic objective (minimizing total system costs) and environmental target (reducing GHG emissions) could help reflect the multi-objective feature of the community-scale energy system.

Table 11
Transportational energy consumptions (PJ).

	Season	1	2	3	4	5
Gasoline-BAU	Winter	[1.994, 2.505]	[2.119, 2.666]	[2.252, 2.838]	[2.399, 3.068]	[2.584, 3.292]
	Summer	[2.014, 2.531]	[2.143, 2.695]	[2.279, 2.872]	[2.435, 3.113]	[2.624, 3.342]
Gasoline-Case 1	Winter	[1.994, 2.505]	[2.119, 2.666]	[2.252, 2.838]	[2.399, 2.982]	[2.256, 2.830]
	Summer	[2.014, 2.531]	[2.143, 2.695]	[2.279, 2.872]	[2.435, 3.026]	[2.289, 2.872]
Gasoline-Case 2	Winter	[1.994, 2.505]	[2.119, 2.666]	[2.252, 2.838]	[2.194, 2.751]	[2.256, 2.830]
	Summer	[2.014, 2.531]	[2.143, 2.695]	[2.279, 2.872]	[2.224, 2.788]	[2.289, 2.872]
Diesel-BAU	Winter	[0.395, 0.488]	[0.424, 0.524]	[0.454, 0.562]	[0.488, 0.609]	[0.547, 0.679]
	Summer	[0.397, 0.491]	[0.426, 0.527]	[0.457, 0.565]	[0.509, 0.634]	[0.551, 0.685]
Diesel-Case 1	Winter	[0.395, 0.488]	[0.424, 0.524]	[0.454, 0.562]	[0.488, 0.599]	[0.512, 0.631]
	Summer	[0.397, 0.491]	[0.426, 0.527]	[0.457, 0.565]	[0.509, 0.625]	[0.515, 0.635]
Diesel-Case 2	Winter	[0.395, 0.488]	[0.424, 0.524]	[0.454, 0.562]	[0.467, 0.576]	[0.512, 0.631]
	Summer	[0.397, 0.491]	[0.426, 0.527]	[0.457, 0.565]	[0.488, 0.601]	[0.515, 0.635]

Table 12
Annual greenhouse-gas emissions (ktonnes).

	Season	1	2	3	4	5
Residential-BAU	Winter	[221.66, 243.83]	[275.66, 305.66]	[297.15, 330.75]	[319.15, 356.40]	[343.27, 384.60]
	Summer	[23.66, 26.06]	[25.77, 28.35]	[25.77, 28.35]	[25.77, 28.35]	[25.77, 28.35]
Residential-Case 1	Winter	[221.66, 243.83]	[275.66, 305.66]	[199.61, 211.56]	[163.70, 175.38]	[167.57, 178.44]
	Summer	[23.66, 26.06]	[25.77, 28.35]	0	0	0
Residential-Case 2	Winter	[221.66, 243.83]	[275.66, 305.66]	[73.11, 76.03]	[76.88, 79.60]	[61.54, 64.30]
	Summer	[23.66, 26.06]	[25.77, 28.35]	0	0	0
Commercial-BAU	Winter	[141.26, 155.39]	[151.15, 166.27]	[161.62, 177.80]	[175.01, 192.16]	[185.11, 203.27]
	Summer	[4.66, 5.13]	[4.99, 5.49]	[5.34, 5.87]	[5.71, 6.28]	[6.11, 6.72]
Commercial-Case 1	Winter	[141.26, 155.39]	[151.15, 166.27]	[146.27, 161.33]	[155.40, 169.83]	[169.25, 184.76]
	Summer	[4.66, 5.13]	[4.99, 5.49]	0	0	[0.40, 0.44]
Commercial-Case 2	Winter	[141.26, 155.39]	[151.15, 166.27]	[128.19, 128.33]	[129.51, 133.17]	[130.70, 130.80]
	Summer	[4.66, 5.13]	[4.99, 5.49]	0	0	0
Transportation-BAU	Winter	[167.23, 209.56]	[178.03, 223.27]	[189.14, 237.98]	[202.09, 250.69]	[219.16, 270.93]
	Summer	[168.80, 211.51]	[179.85, 225.53]	[191.55, 240.59]	[206.08, 255.57]	[222.25, 274.69]
Transportation-Case 1	Winter	[167.23, 209.56]	[178.03, 223.27]	[189.44, 237.98]	[202.09, 250.69]	[193.74, 242.33]
	Summer	[168.80, 211.51]	[179.85, 225.53]	[191.55, 240.59]	[206.08, 255.57]	[196.31, 245.51]
Transportation-Case 2	Winter	[167.23, 209.56]	[178.03, 223.27]	[189.44, 237.98]	[186.31, 232.93]	[193.74, 242.33]
	Summer	[168.80, 211.51]	[179.85, 225.53]	[191.55, 240.59]	[189.79, 237.23]	[196.31, 245.51]
Total GHG-BAU	Winter	[530.15, 608.77]	[604.74, 695.10]	[648.20, 746.53]	[696.26, 799.25]	[747.54, 858.80]
	Summer	[197.12, 242.70]	[210.61, 259.36]	[222.66, 274.81]	[237.56, 290.19]	[254.13, 309.76]
Total GHG-Case 1	Winter	[530.15, 608.77]	[604.74, 695.10]	[535.72, 610.88]	[521.20, 595.91]	[530.66, 605.53]
	Summer	[197.12, 242.70]	[210.61, 259.36]	[191.55, 240.59]	[206.08, 255.57]	[196.71, 245.94]
Total GHG-Case 2	Winter	[530.15, 608.77]	[604.74, 695.10]	[390.74, 442.34]	[392.51, 445.70]	[385.98, 437.42]
	Summer	[197.12, 242.70]	[210.61, 259.36]	[191.55, 240.59]	[189.79, 237.23]	[196.31, 245.51]

For energy consumption by residential and commercial sectors, this study provided projections of the energy demands based on social and economic conditions in the City of Waterloo. However, the climate change impacts on residential and commercial demands were not taken into consideration. The increase of temperature would result in more energy consumption for space cooling in the summer, and less energy use for space heating in the winter. The decrease of heating-energy demands might not be able to offset the increased cooling-energy demands, since they are required in different seasons. Thus, integration of the climate change impacts within an energy systems planning process is complicated and will be an important task for future studies.

In this study, one of the effective approaches for the Waterloo's energy system in adapting to GHG-emission reduction would be the replacement of fossil fuel with electricity, as emission associated with electricity is assumed to be generated at the location of power plants, which are out of the community. However, if Waterloo is inclined to contribute itself to the provincial GHG-emission reduction task, such an assumption may exclude the community to do so. Correspondently, electricity might not the best option for GHG-emission reduction. In this case, various technologies that have higher-energy efficiencies or utilize renewable energy would be considered. In addition, the model would favour cutting of end-user demands, through effective demand management in residential, commercial and transportation sectors. For example, insulation improvement of an attic, wall, foundation and air tightness of doors and windows in old commercial and residential buildings

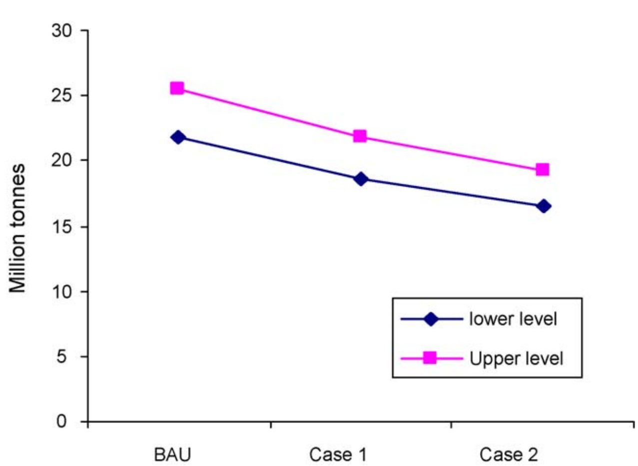

Fig. 5. Total GHG emissions by cases.

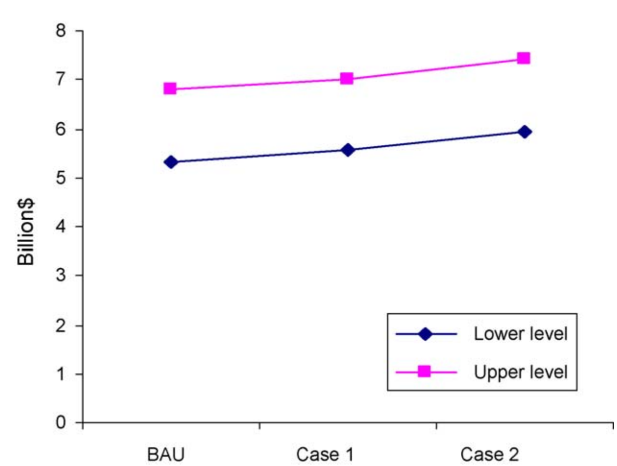

Fig. 6. Total discounted system cost by cases.

would help reduce the energy demands of space heating and cooling.

4. Conclusions

In this study, a DIP-CEM was developed for supporting energy systems planning and environmental management under uncertainty. Through integrating mixed-integer and interval-parameter linear programming methods within a general optimization framework, the developed methodology can tackle uncertainties expressed as interval values and dynamics of capacity-expansion issues. DIP-CEM was then applied to the City of Waterloo, Canada to demonstrate its applicability in supporting decisions of energy systems planning and environmental management. One BAU and two GHG-emission reduction cases were analyzed with desired plans for energy supply and demand and GHG-emission reduction being generated. The results indicated that the developed DIP-CEM could help provide sound strategies for dealing with issues of sustainable energy development and GHG-emission reduction within an energy management system.

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Appendix A. Notations

a set of technologies excluding heat and electricity transmission and generation ($a = c + cz + r + u + v$)
b set of technologies for electricity and heat generation ($b = p + h$)
c average speed of vehicles in road for external transportation
ae alias of ee
cm set of commercial energy demands
cn set of technologies or devices for commercial energy demands
cz set of commercial services by type
cy set of commercial buildings by age
d set of road and rail for external transportation ($d = o + g$)
e set of energy carriers excluding heat
ee set of energy carriers excluding electricity and heat
eh all energy carriers
g rail for train
h set of central heat generation technologies
i set of energy-saving construction technologies
j set of repairing options for existing residential building
l option of train
m set of residential energy demands
n set of technologies or devices for residential energy demands
o roads for external transportation
op capacity-expansion option
p set of electricity conversion technologies
q set of emissions
r set of energy processing technologies
s season of year in a period (i.e. winter and summer)
t time period
u set of freight vehicle by type
v set of passenger vehicle by type
w sources of energy supplies
z set of residential buildings by type
y set of residential buildings by age
'ch' central heating technology
'ele' energy carrier of electricity
'h' energy carrier of heat
'nb' new residential building
'sch' residential space heating and cooling
'sh' space heating
'spc' space heating and cooling

Decision variables

$XCA^{\pm}_{t-1,s,a}$ expanded capacity of technology excluding heat and electricity generation and transmission (PJ)
$XCA^{\pm}_{t,s,z,y,m,n}$ expanded capacity of demand technology (PJ)
$XCA^{\pm}_{t,s,cz,cy,cm,cn}$ expanded capacity of commercial energy demand technology (PJ)
$XCA^{\pm}_{t-1,s,r}$ expanded capacity of energy processing technology (PJ)
$XD^{\pm}_{t,s,z,y,m,n}$ activity of residential demand technology (PJ)
$XD^{\pm}_{t,s,cz,cy,cm,cn}$ activity of commercial demand technology (PJ)
$XDTE^{\pm}_{t,s,v,o,c}$ activity of external goods transportation (million km tonne)
$XDTE^{\pm}_{t,s,u,o,c}$ activity of external passenger transportation (million km $\times$ person)
$XDTI^{\pm}_{t,s,u}$ activity of internal goods transportation (million km tonne)
$XDTI^{\pm}_{t,s,v}$ activity of internal passenger transportation (million km $\times$ person)
$XE^{\pm}_{t,s,p}$ production of electricity from power-generation technology (PJ)
$XEE^{\pm}_{t,s,w}$ amount of exported electricity (PJ)
$XEH^{\pm}_{t,s,w}$ amount of exported heat (PJ)
$XES^{\pm}_{t,s,e,w}$ amount of exported energy carrier (PJ)
$XH^{\pm}_{t,s,h}$ production of heat from heat-generation technology (PJ)
$XIE^{\pm}_{t,s,w}$ amount of imported electricity (PJ)
$XIH^{\pm}_{t,s,w}$ amount of imported heat (PJ)
$XIS^{\pm}_{t,s,e,w}$ amount of imported energy carrier (PJ)
$XP^{\pm}_{t,s,r}$ activity of process technology (PJ)
$XS^{\pm}_{t,s}$ set of all continuous decision variables
$XSE^{\pm}_{t,s,z,y='nb',m='spc',n}$ activity of energy-saving construction option (PJ)
$XSR^{\pm}_{t,s,z,y\neq'nb',m='spc',n}$ activity of insulation improvement option (PJ)
$YCB^{\pm}_{t-1,s,b,op}$ capacity-expansion option for heat and electricity generation
$YCB^{\pm}_{t-1,s,d,op}$ capacity-expansion option of road and rail for external transportation
$YCB^{\pm}_{t-1,s,p,op}$ capacity-expansion option for power generation technology
$YCB^{\pm}_{t-1,s,h,op}$ capacity-expansion option for central heat generation technology
$YCE^{\pm}_{t,s,p,op}$ capacity-expansion option for domestic electricity transmission
$YCE^{\pm}_{t,s,w,op}$ capacity-expansion option for imported electricity transmission
$YCH^{\pm}_{t,s,h,op}$ capacity-expansion option for domestic heat transportation
$YCH^{\pm}_{t,s,p,op}$ capacity-expansion option for co-generated heat transportation

$YCH^{\pm}_{t,s,w,op}$	capacity-expansion option for imported heat transportation
$YC^{\pm}_{t,s}$	set of all discrete decision variables.

Parameters

$AENV^{\pm}_{t,q}$	annual emission target (million tonnes)
$AF^{\pm}_{t,s,z,y,m,n}$	available factor of residential demand technology or device
$AF^{\pm}_{t,s,cz,cy,cm,cn}$	available factor of commercial demand technology or device
$AF^{\pm}_{t,s,o}$	available factor of road capacity for external transportation (vehicle)
$AF^{\pm}_{t,s,g}$	available factor of rail capacity for external transportation (vehicle)
$AF^{\pm}_{t,s,p}$	available factor of power technology
$AF^{\pm}_{t,s,h}$	available factor of central heating technology
$AF^{\pm}_{t,s,r}$	available factor of energy processing technology
$ATFE^{\pm}_{t,s,p}$	available factor of transmission for domestic electricity
$ATFE^{\pm}_{t,s,w}$	available factor of transmission for imported electricity
$ATFH^{\pm}_{t,s,h}$	available factor of transmission for domestic central heat
$ATFH^{\pm}_{t,s,p}$	available factor of transmission for heat from co-generated power plant
$ATFH^{\pm}_{t,s,w}$	available factor of transmission for imported central heat
$AVL^{\pm}_{t,s,v}$	average travel length for internal passenger transportation (km)
$AVL^{\pm}_{t,s,u}$	average travel length for internal goods transportation (km)
$AVK^{\pm}_{t,s,v,o}$	average travel length for external passenger transportation (km)
$AVK^{\pm}_{t,s,u,o}$	average travel length for external goods transportation (km)
$CB^{\pm}$	scale capacity of expansion option for heat and electricity generation (PJ)
$CB^{\pm}$	scale capacity of expansion option for external road and rail (PJ)
$CER^{\pm}_{t,s,z,y=\text{'}nb\text{'},m=\text{'}spc\text{'},n}$	cost for insulation improvement option (million\$/PJ)
$CES^{\pm}_{t,s,z,y=\text{'}nb\text{'},m=\text{'}spc\text{'},n}$	cost of energy-saving construction technology (million\$/PJ)
$CET^{\pm}_{t,s,p,op}$	scale capacity of expansion option for domestic electricity transmission (PJ)
$CET^{\pm}_{t,s,w,op}$	scale capacity of expansion option for imported electricity transmission (PJ)
$CHT^{\pm}_{t,s,h,op}$	scale capacity of expansion option for domestic heat transportation (PJ)
$CHT^{\pm}_{t,s,p,op}$	scale capacity of expansion option for co-generated heat transportation (PJ)
$CHT^{\pm}_{t,s,w,op}$	scale capacity of expansion option for imported heat transportation (PJ)
$COH^{\pm}_{t,s,p,\text{'}h\text{'}}$	coefficient of heat production from co-generation power technology
$CR^{\pm}_{t,s}$	set of residual capacities of all technologies
$CRD^{\pm}_{t,s,z,y,m,n}$	residual capacity of residential demand technology and device (PJ)
$CRD^{\pm}_{t,s,cz,cy,cm,cn}$	residual capacity of commercial energy demand technology (PJ)
$CRD^{\pm}_{t,s,v}$	existing capacity of passenger vehicle (million vehicle)
$CRD^{\pm}_{t,s,u}$	existing capacity of freight vehicle (million vehicle)
$CRD^{\pm}_{t,s,o}$	existing capacity of road (million car equivalent)
$CRD^{\pm}_{t,s,g}$	existing capacity of rail (train shift)
$CRD^{\pm}_{t,s,p}$	residual capacity of power technology (PJ)
$CRD^{\pm}_{t,s,h}$	residual capacity of central heating technology (PJ)
$CRD^{\pm}_{t,s,r}$	residual capacity of energy processing technology (PJ)
$CRDA^{\pm}_{t,s,a}$	residual capacity of technology excludes heat and electricity technology (PJ)
$CRDE^{\pm}_{t,s,w}$	residual capacity of electricity transmission facility (PJ)
$CRDE^{\pm}_{t,s,p}$	residual capacity of transmission for domestic generated electricity (PJ)
$CRDH^{\pm}_{t,s,h}$	residual capacity of transmission for domestic central heat (PJ)
$CRDH^{\pm}_{t,s,p}$	residual capacity of transmission for heat from co-generated power plant (PJ)
$CRDH^{\pm}_{t,s,w}$	residual capacity of transmission for imported central heat (PJ)
$DEL^{\pm}_{t,s,r,e}$	delivery cost of energy carriers for energy processing generation (million\$/PJ)
$DEL^{\pm}_{t,s,p,ee}$	delivery cost of energy carriers for electricity generation (million\$/PJ)
$DEL^{\pm}_{t,s,h,e}$	delivery cost of energy carriers for heat generation (million\$/PJ)
$DEL^{\pm}_{t,s,z,y,m,n,e}$	delivery cost of energy carriers for residential demand (million\$/PJ)
$DEL^{\pm}_{t,s,cz,cy,cm,cn,eh}$	delivery cost of energy carriers for commercial demand (million\$/PJ)
$DELE^{\pm}_{t,s,e,w,ee}$	delivery cost of energy carrier for energy carrier exports (million\$/PJ)
$DELI^{\pm}_{t,s,e,w,ee}$	delivery cost of energy carrier for energy carrier imports (million\$/PJ)
$DELT^{\pm}_{t,s,v,e}$	delivery cost of energy carrier for internal passenger transportation (million\$/PJ)
$DELT^{\pm}_{t,s,v,o,e}$	delivery cost of energy carrier for external passenger transportation (million\$/PJ)
$DELT^{\pm}_{t,s,u,e}$	delivery cost of energy carrier for internal goods transportation (million\$/PJ)
$DELT^{\pm}_{t,s,u,o,e}$	delivery cost of energy carrier for external goods transportation (million\$/PJ)
$DMR^{\pm}_{t,s,z,y,m}$	residential energy demand (PJ)
$DMC^{\pm}_{t,s,cz,cy,cm}$	commercial energy demand (PJ)
$ENV^{\pm}_{t,s,r,q}$	emission coefficient of energy processing activity (ktonnes)
$ENV^{\pm}_{t,s,p,q}$	emission coefficient of electricity generation activity (ktonnes)
$ENV^{\pm}_{t,s,h,q}$	emission coefficient of central heat generation activity (ktonnes)
$ENV^{\pm}_{t,s,z,y,m,n,q}$	emission coefficient of residential demand activity (ktonnes)
$ENV^{\pm}_{t,s,cz,cy,cm,cn,q}$	emission coefficient of commercial demand activity (ktonnes)
$ENV^{\pm}_{t,s,v,q}$	emission coefficient of passenger vehicle for internal transportation (ktonnes)

$ENV^{\pm}_{t,s,u,q}$ emission coefficient of freight vehicle for internal transportation (ktonnes)
$ENV^{\pm}_{t,s,u,o,c,q}$ emission coefficient of for external passenger vehicle (ktonnes)
$ENV^{\pm}_{t,s,v,o,c,q}$ emission coefficient of freight vehicle for external transportation (ktonnes)
$EOUT^{\pm}_{t,s,z,y,m,n}$ output efficiency of residential demand technology
$EOUT^{\pm}_{t,s,cz,cy,cm,cn}$ output efficiency of commercial energy demand technology
$EP^{\pm}_{t,w,ee,w}$ price of exported energy carrier (million$/PJ)
$EPE^{\pm}_{t,s,w}$ price of exported electricity (million$/PJ)
$EPH^{\pm}_{t,s,w}$ price of exported heat (million$/PJ)
$ES_{t,s}$ set of all energy resources
$ESR^{\pm}_{t,s,z,y,m,i}$ efficiency of energy-saving construction technology (PJ)
$ESR^{\pm}_{t,s,z,y,m,j}$ efficiency of insulation improvement option for residential building (PJ)
$ETIN^{\pm}_{t,s,p,op}$ investment cost of transmission for domestic electricity (million$/PJ)
$ETIN^{\pm}_{t,s,w,op}$ investment cost of transmission for imported electricity (million$/PJ)
$FIX^{\pm}_{t,s,a}$ fixed cost of technology excludes heat and electricity transmission and generation (million$/PJ)
$FIX^{\pm}_{t,s,b}$ fixed cost of heat and electricity generation (million$/PJ)
$GOTE^{\pm}_{t,s}$ external transportation for passenger (million person)
$GOTI^{\pm}_{t,s}$ internal transportation for goods (million tonnes)
$HTIN^{\pm}_{t,s,h,op}$ investment cost of transmission for domestic generated heat (million$/PJ)
$HTIN^{\pm}_{t,s,p,op}$ investment cost of transmission for co-generated heat (million$/PJ)
$HTIN^{\pm}_{t,s,w,op}$ investment cost of transmission for imported heat (million$/PJ)
$INC^{\pm}_{t,s,a}$ investment cost of technology excluding heat and electricity generation and transportation (million$/PJ)
$INC^{\pm}_{t-1,s,b,op}$ investment cost of heat and electricity generation technology (million$/PJ)
$INC^{\pm}_{t-1,s,d,op}$ investment cost of road and rail for external transportation (million$/PJ)
$INP^{\pm}_{t,s,r,e}$ inputs of energy carriers for energy processing technologies
$INP^{\pm}_{t,s,p,ee}$ inputs of energy carriers for electricity conversion technologies
$INP^{\pm}_{t,s,h,e}$ inputs of energy carriers for central heat generation technologies
$INP^{\pm}_{t,s,z,y,m,n,eh}$ inputs of energy carrier for residential demand technology
$INP^{\pm}_{t,s,cz,cy,cm,cn,eh}$ inputs of energy carrier for commercial demand technology
$INP^{\pm}_{t,s,v,e}$ inputs of energy carrier for internal passenger transportation
$INP^{\pm}_{t,s,u,e}$ inputs of energy carrier for internal goods transportation
$INPE^{\pm}_{t,s,e,w,ee}$ inputs of energy carriers for energy exports
$INPI^{\pm}_{t,s,e,w,ee}$ inputs of energy carriers for energy imports
$INPR^{\pm}_{t,s,v,o,c,e}$ inputs of energy carrier for external passenger transportation
$INPR^{\pm}_{t,s,u,o,c,e}$ inputs of energy carrier for external goods transportation
$IP^{\pm}_{t,s,ee,w}$ price of imported energy carrier (million$/PJ)
$IPE^{\pm}_{t,s,w}$ price of imported electricity (million$/PJ)
$IPH^{\pm}_{t,s,w}$ price of imported heat (million$/PJ)
$LB^{\pm}_{t,s}$ lower bound value
$POTE^{\pm}_{t,s}$ external transportation for passenger (million person)
$POTI^{\pm}_{t,s}$ internal transportation for passenger (million person)
$PPVE^{\pm}_{t,s,v}$ efficiency of passenger vehicle for external transportation (person/vehicle)
$PPVE^{\pm}_{t,s,u}$ efficiency of freight vehicle for external transportation (tonne/vehicle)
$PPVI^{\pm}_{t,s,v}$ efficiency of passenger vehicle for internal transportation (person/vehicle)
$PPVI^{\pm}_{t,s,u}$ efficiency of freight vehicle for internal transportation (tonne/vehicle)
$T1^{\pm}_{t,s,o}$ the maximum capacity of road when average speed of vehicle = ν_1 km/hr
$T2^{\pm}_{t,s,o}$ the maximum capacity of road when average speed of vehicle = ν_2 km/hr
$T3^{\pm}_{t,s,o}$ the maximum capacity of road when average speed of vehicle = ν_3 km/hr
$TEFIX^{\pm}_{t,s,w}$ fixed cost of transmission for electricity import (million$/PJ)
$TEFIX^{\pm}_{t,s,p}$ fixed cost of transmission for domestic generated electricity (million$/PJ)
$THFIX^{\pm}_{t,s,p}$ fixed cost of transmission for co-generated heat (million$/PJ)
$THFIX^{\pm}_{t,s,w}$ fixed cost of transmission for heat import (million$/PJ)
$THFIX^{\pm}_{t,s,h}$ fixed cost of transmission for domestic generated electricity (million$/PJ)
$UB^{\pm}_{t,s}$ upper bound values
$VRC^{\pm}_{t,s,r}$ variable cost of energy processing technology (million$/PJ)
$VRC^{\pm}_{t,s,cz,cy,cm,cn}$ variable cost of commercial demand technology (million$/PJ)
$VRC^{\pm}_{t,s,u}$ variable cost of freight vehicle for internal transportation (million$/PJ)
$VRC^{\pm}_{t,s,u,o}$ variable cost of freight vehicle for external transportation (million$/PJ)
$VRE^{\pm}_{t,s,p}$ variable cost of electricity generation technology (million$/PJ)
$VRH^{\pm}_{t,s,h}$ variable cost of central heating technology (million$/PJ).

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